THE GEOCHEMICAL EVOLUTION OF THE ALKALINE AND CARBONATITE COMPLEXES OF THE DAMARALAND IGNEOUS PROVINCE, SOUTH WEST AFRICA.

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View of Ondurakorume looking south

View of Etaneno looking westwards

ABSTRACT

The Damaraland igneous province in northern South West Africa contains basalt/granite, alkaline, peralkaline and carbonatite complexes. The geochemical features of the Okorusu, Kalkfeld, Ondurakorume and Osongombo carbonatite complexes and the peralkaline Etaneno complex form the main thesis of this study. X-ray fluorescence electron microprobe and wet chemical methods were used to establish the behaviour of major and trace elements (Nb, Zr, Y, Sr, Rb, Ba, Ce, Nd, La, Cl and F) during the formation of these complexes.

The two largest carbonatite complexes, namely Okorusu and Kalkfeld, consist of confocal rings of syenite and nepheline syenite into which smaller plugs of carbonatite were emplaced. An early phase of Na-Fe fenitization occurred at both complexes and resulted in the formation of aegirine granites and syenites at Kalkfeld and a massive pyroxene fenite at Okorusu. At Okorusu this initial fenitization was followed by extensive brecciation and feldspathization. Syenitic rocks of Kalkfeld also underwent K-metasomatism. Concentrations of hematite ore (Kalkfeld, Osongombo, Okorusu), rare earth minerals (Ondurakorume), apatite (Ondurakorume) and fluorite (Okorusu) are of potential or actual economic importance.

Plots of oxides and trace elements versus differentiation index, K/Rb plots and plots on diagrams such as Qz-Ne-Kp and SiO_2-Al_2O_3-Na_2O+K_2O suggest that fractionation of feldspar and nepheline (also plagioclase at Etaneno) occurred during the evolution of the alkaline magmas at these complexes. The alkaline rocks of Okorusu are much more Na- and volatile-rich than similar rocks of Kalkfeld and Ondurakorume. These

high concentrations might be connected with the relatively high REE contents of the Okorusu alkaline rocks and the relatively low REE contents of their associated carbonatitic rocks. Most of the carbonatitic rocks from the Kalkfeld group of complexes are highly enriched in the rare earth elements. Major and trace element contents show that the partly fenitized granite ring at Kalkfeld does not, as previously thought, belong to the alkaline suite but that it represents wallrocks of Salem granite. It is suggested that at both Kalkfeld and Okorusu sodium loss during fenitization drove the composition of the magmas from the ijolitic cotectic in the system Na_2O-Al_2O_3-Fe_2O_3-SiO_2, into the oxide field. This resulted in an increase in the precipitation of magnetite as indicated by the increase in modal magnetite in the rocks with lower Na_2O contents.

The fenitized rocks at Kalkfeld and Okorusu display trace element (Zr, Sr, Rb, Ba, F and Cl) as well as REE contents which are similar to those of their associated alkaline rocks while the concentration of these elements in feldspathized rocks corresponds to that of their associated carbonatitic rocks. The early phase of Na-metasomatism is thus considered to have been caused by fluids escaping from the crystallizing silicate magmas while the later phase of feldspathization apparently resulted from a K-CO_2-rich fluid in equilibrium with the carbonate magma. A similar distinction between Na and K-metasomatism is suggested by an investigation of the chemical trends displayed by analysed fenites from other alkaline/carbonatite complexes.

The carbonatite plugs of Kalkfeld and Ondurakorume consist of multiple intrusions that are of magmatic origin. Their major element contents vary regularly with the relative age of the intrusions within each complex, as can be expected if fractionation processes were operative.

Leucocratic globules occur in monchiquite dykes at Okorusu and in highly altered micaceous rocks at Ondurakorume and Kalkfeld. These globules consist mainly of calcite, sodalite and/or analcite and lesser amounts of K-feldspar and phlogopite. They become more siliceous as they increase in size. Their shape and texture suggest that they could have formed by a process of liquid immisci= bility. This feature, together with the different chemical trends (SrO/CaO and CaO + MgO versus a diferrentiation parameter) exhibited by the alkaline and carbonatitic rocks, strongly indicate that the two magma types responsible for the alkaline/carbonatite complexes, followed individual fractionation paths after their separation as two immiscible liquids.

Chemical variation diagrams of the available analyses of Damaraland igneous rocks (e.g. total alkalies versus silica), indicate that a hypersthene normative tholeiitic magma was parental to the basic complexes whereas the carbonatitic complexes originated through the differentiation of a nephelinitic magma.

The major element chemistry of the basic complexes is analogous to that of islands in the Atlantic Ocean. This, together with the fact that their ages correspond to that of the breakup of Gondwana= land, suggest a similar origin for the tholeiitic magmatism on the continent and the nearby magmatic activity of the pristine oceanic ridge. The Damaraland igneous province exhibits a change in com= position from the margin of the continent towards the interior. Basic complexes are found near the coast whereas further inland the complexes become alkalic and/or carbonatitic. A similar pattern is shown to exist for the predominantly alkaline/carbonatite complexes of Angola; including clusters of kimberlite pipes. In fact, the

Damaraland province is just one of a series of parallel linear igneous provinces along the southwest coast of Africa. Their position can be correlated with unique fracture zones which off= set the Mid Atlantic ridge and their petrologic variation is ten= tatively ascribed to warp axes parallel to the continental margin. The same relationship seems to exist between plate tectonic rup= turing of a continent and linear zones of igneous activity in Greenland, India, North and South America.

How odd is it that anyone should not see
that all observations must be for or against
some view, if it is to be of any service.

Charles R. Darwin

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1 GENERAL GEOLOGY

1.1 INTRODUCTION

Alkaline magmatism occurred in the form of central complexes in a number of northeast-trending lineaments along the west coast of Africa. Marsh (1973) suggested that these lineaments can be correlated with unique fracture zones that offset the Mid-Atlantic ridge. The majority of these complexes are considered to be of an age (Table 1) which corresponds to that proposed for the early opening of the South Atlantic by Le Pichon and Hayes (1971) and Hertz (1977). This suggests that their emplacement as well as the outflow of the Etendeka tholeiites (115 m.y.) might be related to the disruption of Gondwanaland.

One of the best defined linear provinces is situated between the Ugab and the Khan rivers in the Damaraland region of South West Africa. Petrographically this province shows considerable variation. Ultramafic to oversaturated as well as some alkaline-carbonatitic associations are present. The Angolan provinces to the north contain more carbonatitic complexes whereas the Lüderitz province further south is apparently devoid of the granite-basalt association.

Martin, et al. (1960) grouped the Damaraland complexes as follows:

A. The Granite Plutons: Brandberg, Erongo, Gross and Klein Spitzkoppe and an intrusive granitic mass 90 km east of Omaruru. The Spitzkoppe and the Omaruru granite have not been unequivocally proven as belonging to this suite and were omitted by Mathias (1974) in her summary.

B. The differentiated basic complexes:

Cape Cross, Doros
Okonjeje and Messum.

C. The carbonatitic and peralkaline complexes:

Ondurakorume, Osongombo and Okorusu (carbonatitic)
Paresis and Etaneno (peralkaline).

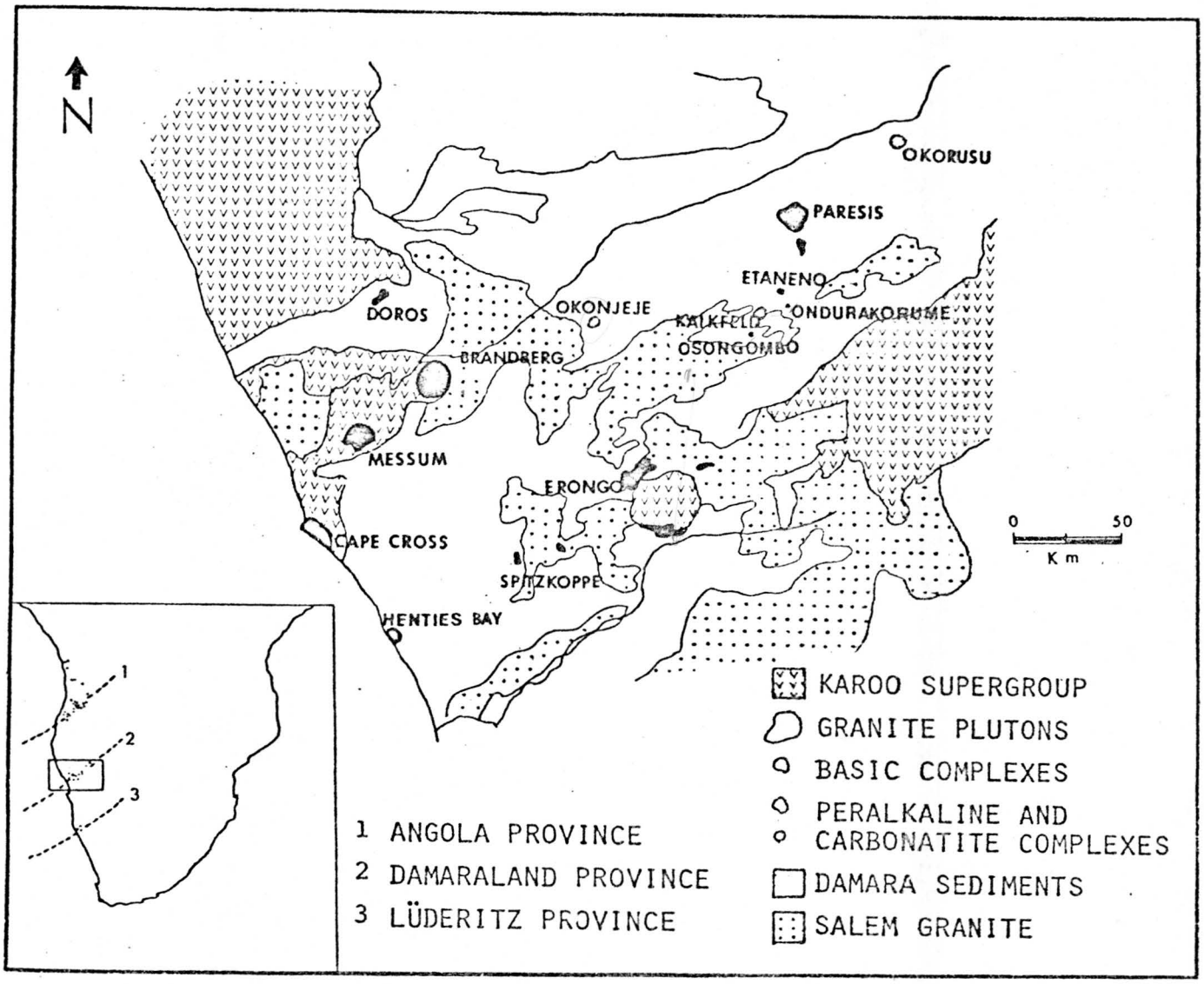


Fig. 1. The Damaraland alkaline province (after Martin, et al., 1960) The inset shows the location of the Angolan (1), Damaraland (2) and Lüderitz (3) alkaline provinces.

The granite plutons vary in size from a few kilometres (Spitzkoppe) to more than 30 kilometres (Brandberg) in diameter and are wellknown landmarks in the area. The basic complexes are of a more uniform size (5-15 km), Paresis measures 18 kilometres in diameter and the other peralkaline and carbonatite complexes are much smaller. All these instrusions form prominent hills ex= cept Okorusu and Kalkfeld where fenitized wallrocks build the major topography.

Alkaline rocks which probably belong to a complex similar in nature to that at Cape Cross have recently been discovered near Henties Bay (R. McG. Miller, per= sonal communication). An elongated body of picrite occurs 40 km east of Outjo and has been regarded by Martin (1963) as belonging to this province but subse= quent investigation by mining companies lead to the belief (Söhnge, personal communication) that these rocks belong to the Karoo dolerite suite.

1.1.1 Previous work

The existence of a major intrusive cycle in the Damara region of South West Africa was known at the beginning of the century. Cloos (1919) recognized the intrusive nature of the Brandberg and Erongo complexes and established their post-Karoo age. A few year later Reuning and Von Huene (1925) estab= lished a similar age from fossil evidence for the Doros volcano and the Kaoko Beds. Further discoveries followed so that 12 major occurrences were included in the summary by Martin, et al. (1960).

The most recent investigations are tabulated in Table 1.

TABLE 1: Important contributions on the geology of the Damaraland igneous complexes. Age determinations after Siedner and Miller (1968) and Manton and Siedner (1967).

Damaraland ring Complexes	Author	Preferred age (m.y.)	Rock type dated
Cape Cross	Linning (1968)		
Messum	Korn and Martin (1954) Mathias (1956,1957)	123	basalt
Doros	Hodgson and Botha (1974)	125 123	gabbro ring dyke plagioclase from gabbro
Brandberg			
Erongo	Cloos (1919)		
Paresis	Siedner (1965)	136 135	basalt comendite
Kalkfeld	Van Zijl (1962) Verwoerd (1967)		
Ondurakorume	Verwoerd (1967)		
Osongombo	Verwoerd (1967)		
Okorusu	Van Zijl (1962) Verwoerd (1967)		
Okonjeje	Simpson (1954)	164	gabbro
Kaoko Lavas			
Etendeka Plateau		114	basalt
10 km N-E of Cape Cross		116	basalt
Dykes			
Swakopmund-Karibib road		196	dolerite
9,6 km SW of Okonjeje		128	dolerite
10 km NE of Uis Mine		133	dolerite
12 km S of Cape Cross		163	dolerite
12 km N of Swakopmund		165	dolerite
14 km E of Henties Bay		115	dolerite
14 km N of Swakopmund		129	dolerite
16 km SW of Messum		128	dolerite
17 km SW of Okonjeje		196	dolerite

Apart from the newly discovered Henties Bay complex all others have been mapped and their petrology described in some detail. Investigations of the Etaneno complex by Verwoerd and Retief and the Ondurakorume complex by Key and by Collins have not been published but are referred to by Mathias (1974).

Chemical data are available for some complexes, notably Okonjeje, Messum and Paresis. Very little chemical data are available for the large granitic intrusions while those for the alkaline and carbonatitic complexes are fragmentary.

1.1.2 Scope of the study

A number of important questions are posed by an igneous province which includes rock types ranging from ultrabasic and oversaturated to alkaline and carbonatitic associations.

The present study is concerned mainly with the geochemistry of those complexes which include carbonatites, i.e. Kalkfeld, Okorusu, Ondurakorume and Osongombo. In order to understand their evolution it became necessary to compare their chemistry with that of the other complexes of the province. A study of the peralkaline Etaneno complex was included because the possibility of a genetic link between carbonatitic complexes and such an alkaline complec devoid of carbonatites had to be considered.

In broad terms this study attempts to answer the following questions.

1. What evolutionary trends existed during the development of the Kalkfeld, Okorusu, Osongombo, Ondurakorume and Etaneno alkaline/carbonatite complexes and what processes were responsible therefore?

2. Does a genetic relationship exist between the alkaline/carbonatite complexes and the basaltic and granitic members of the province?

3. What geochemical processes played a role in the formation of the various mineral deposits associated with the carbonatite complexes, viz. iron ore at Kalkfeld and Osongombo, fluorite and iron ore at Okorusu, phosphate and rare-earth deposits at Ondurakorume?

4. What chemical changes were involved during the formation of the contrasting types of fenite associated with the Okorusu and Kalkfeld complexes?

5. Are the Damaraland, Angolan and Lüderitz alkaline provinces geochemically similar and to what extent do they differ from provinces associated with typical rift-zone environments?

6. What is the relationship between the development of alkaline provinces and the tectonic environment associated with crustal separation?

1.2 GEOLOGY

1.2.1 Regional geology

The regional geology of Damaraland has been described by Martin (1965), Smith (1961) and Clifford (1967) with more recent contributions by Guj (1970), Miller (1972), Jacob (1978) and Martin (1977).

The basement rocks into which the post-Karoo complexes were emplaced consist of metamorphosed sediments of the Damara Supergroup. Quartzites, marbles, mica-shists, amphibolites and a prominent tillite horizon are intensely folded along axes with a northeasterly trend. These rocks were deposited in an eugeosyncline which, according to Martin (op.cit.) developed in the classical way rather than through plate tectonics. Its central zone of high grade metamorphism underwent partial melting to produce syn- or late-tectonic granitic units of which the Red granite-gneiss and the Salem granite are the most important. The former unit comprises granitic gneisses which occur mainly in anticlinal structures associated with late stage alaskitic pegmatitic granites. The Salem granite suite usually occupies synclinal structures and consists of three members, viz. a syn-tectonic gneissic margin of biotite-hornblende granite/tonalite/granodiorite, a main phase of gneissic, porphyritic biotite granite and a very late and post-tectonic leucogranite. The latter phase is highly radioactive.

1.2.2 The Granite Intrusions

Martin et al.(1960) regarded the granitic plutons of Brandberg, Erongo and Spitzkoppe as part of the Damaraland igneous province. Mathias (1974) drew attention to the fact that of these complexes only Brandberg has alkaline affinities. However, there is little doubt that all these complexes are of similar age and were emplaced under similar structural control; unfortunately geochemical evidence of a genetic relationship is lacking.

The main intrusion at Brandberg consists of a medium-grained hornblende granite containing some biotite and tourmaline with occasional arfvedsonite. Chemically these rocks show affinities with some of the Paresis lavas (Siedner, 1965b).

1.2.3 The Differentiated Basic Complexes

The Cape Cross, Doros, Okonjeje and Messum complexes are situated in the western part of the province and show some similarity in mineralogy and chemistry. These complexes, except Doros which is entirely gabbroic in composition, are comprised mainly of an early tholeiitic series followed by subordinate alkaline magmatism. Generalized geological maps of these complexes are given in Fig. 2.

CAPE CROSS: Basalts and gabbros form saucer-shaped inward-dipping units which were pierced by a massive granite forming the central part of the complex. Cone sheets of fine-grained nepheline syenite and small plugs of syenite are also present.

OKONJEJE: This complex is well exposed and exhibits two clearly defined fractionation trends, viz. a tholeiitic series which consists essentially of gabbro-picrite ring dykes, layered units of adamellite and subordinate dykes of quartz syenite; and an alkaline series with a centrally situated gabbroic mass, a ring-like unit of oligoclase essexite, small stocks of foyaite and radial dykes of camptonite, monchiquite, alnöite, tinguaite and bostonite.

MESSUM: Tholeiitic lavas, alternating with acid tuffs and agglomerate belong to the initial phase of vulcanicity and form the peripheral hills of the complex. The volcanic activity was followed by the intrusion of olivine dolerite and a later granitic phase. Magmatism culminated in alkaline intrusive activity and resulted in the formation of syenite and tinguaite units as well as a centrally situated foyaite plug. Extensive metasomatism affected most of these rock types.

DOROS: This complex is gabbroic in composition and consists of inward dipping saucer-shaped layers. Of the five periods of intrusion that can be distinguised only one shows signs of magmatic differentiation. Gabbroic and syenitic dykes intrude these layers and are considered to represent injections of residual magma during the final stages of emplacment.

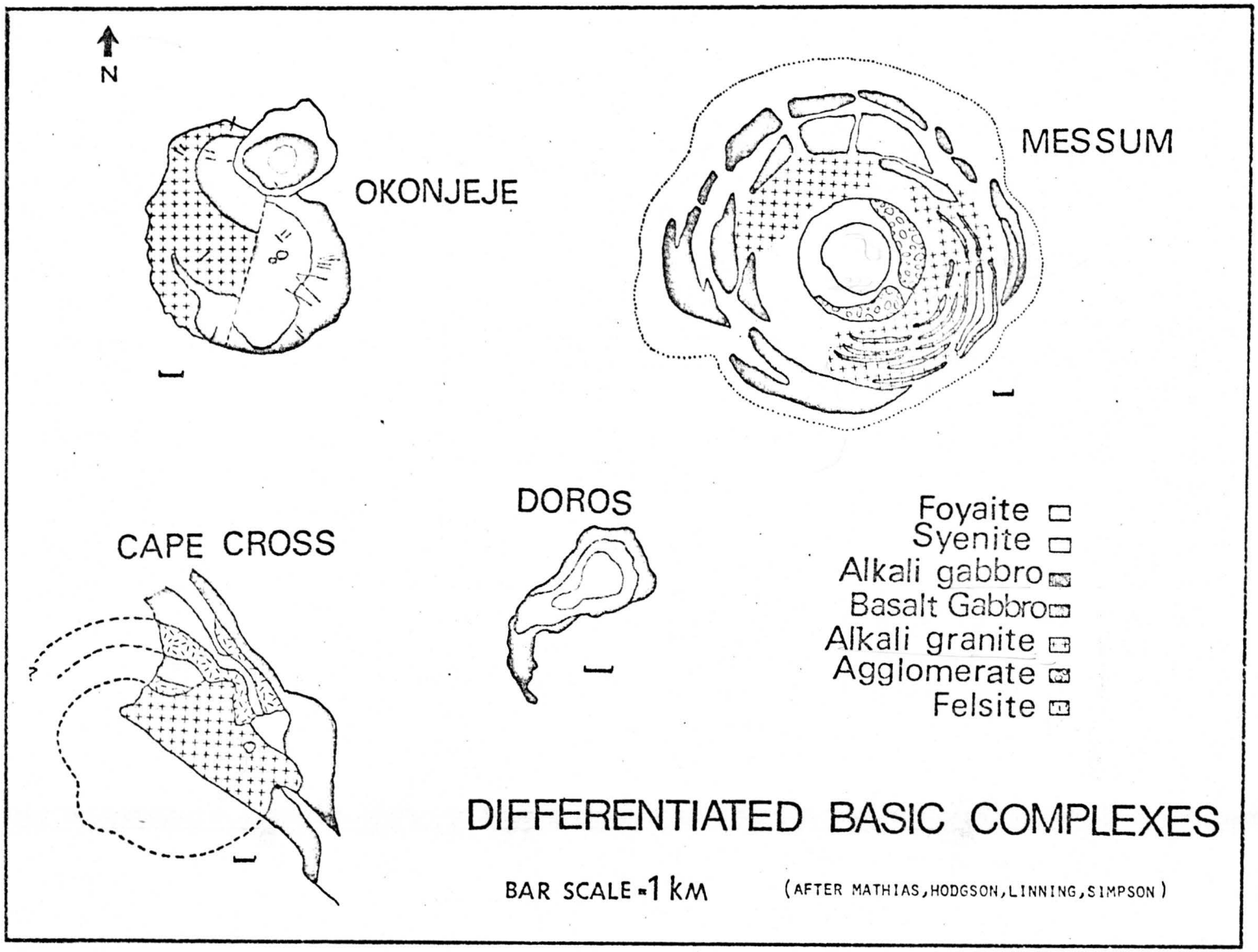


Fig. 2: Generalized geological maps of the differentiated basic complexes of the Damaraland alkaline province.

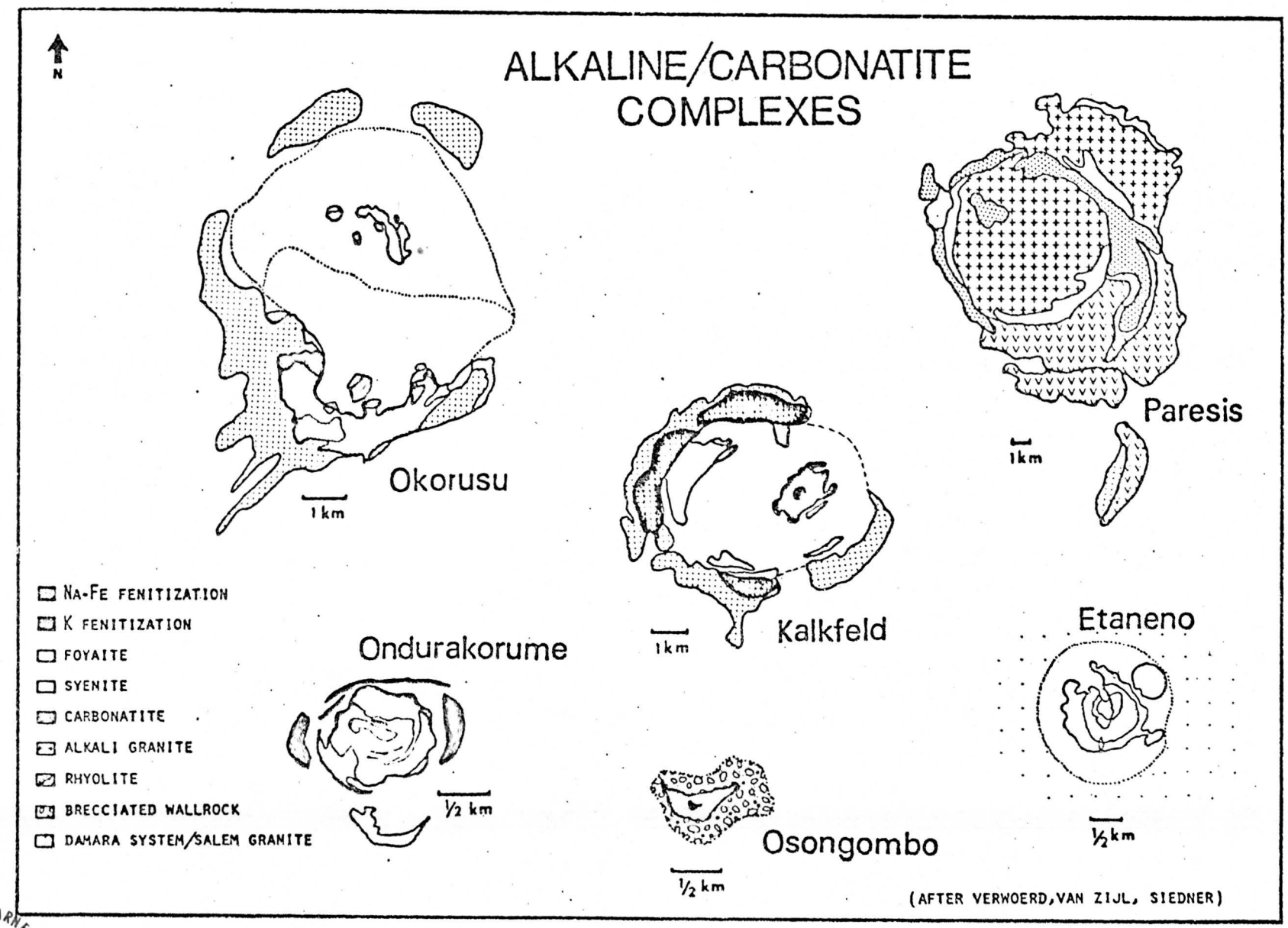


Fig. 3: Generalized geological maps of the carbonatite and peralkaline complexes of the Damaraland alkaline province.

1.2.4 The Peralkaline Complexes

PARESIS: At this complex the earliest phase of igneous activity resulted in the formation of rhyolitic lava flows and dykes. Three cycles, characterized by feldspar rhyolite, quartz-feldspar porphyry and comendite can be distinguised. Following the close of rhyolite vulcanism a suite of alkaline rocks, which range in composition from microgranite through syenite to foyaite, was emplaced as dykes and small plugs.

ETANENO: W.J. Verwoerd mapped this complex during 1965 (Fig. 4) and with A.E. Retief prepared an unpublished account of its petrology and mineralogy. The following description is based on their work, supplemented by geochemical analysis of samples collected for this purpose.

The Etaneno complex is an almost perfectly circular ring complex 2 km in diameter and comprises five undersaturated rock types. Verwoerd (personal communication) suggested the following age relationship on geological and textural grounds:

Rock type

Dark grey and light-coloured nepheline syenite dykes (youngest)
Coarse-grained nepheline syenite
White nepheline syenite
Grey nepheline syenite
Sodalite syenite
Porphyritic (core) nepheline syenite (oldest)

The Core Nepheline Syenite

An oval plug of dark grey porphyritic nepheline syenite with a finer marginal facies occurs near the centre of the complex. Feldspar occurs as phenocrysts (up to 0.4cm in length) and as grains in the groundmass. The phenocrysts are essentially plagioclase and are commonly engulfed by perthite. Nepheline and sodalite occur as individual grains in the groundmass and pyroxene of the diopside-hedenbergite as well as the aegirine-augite series is present. Olivine and iron ore occur sparingly.

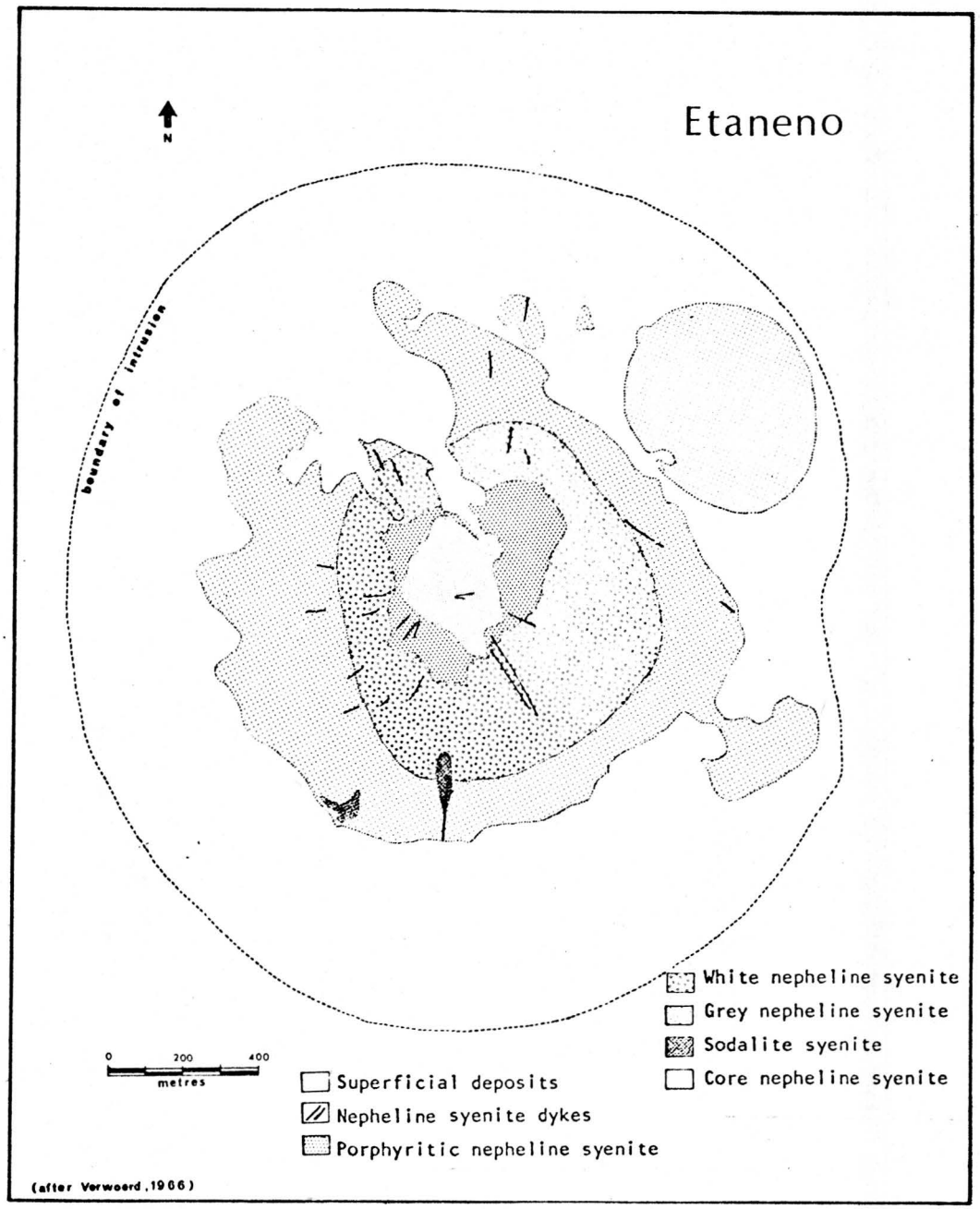


Fig. 4: Geological map of the Etaneno peralkaline complex.

Rounded xenoliths consisting of closely packed pyroxene, nepheline and altered feldspar phenocrysts set in a fine-grained pyroxene, iron ore and feldspar matrix occur sporadically in this unit - they were probably derived from the chilled marginal facies.

The Grey Nepheline Syenite

This unit forms the outermost ring of the complex. It is generally uniform, but at a few localities dark minerals were seen to be concentrated in narrow bands reminiscent of rhythmic layering. Mafic schlieren which occur as single, parallel, bifurcating and "cross-bedded" bands, a few centimeters wide, occur on the eastern slopes of the mountain.

The syenite is medium to coarse-grained. Greenish anorthoclase is closely packed in a matrix of olivine (Fa_{65-100}), pyroxene, amphibole, biotite and magnetite. A first generation nepheline is present as small inclusions in the feldspar whereas a later generation occurs sporadically.

The White Nepheline Syenite

The white nepheline syenite forms a complete ring between the grey and coarse-grained units. It shows very little evidence of internal structure except a few concentrically arranged mafic layers with a near vertical dip. The contact between this unit and the grey nepheline syenite appears to be gradational. Two varieties are present. In the one euhedral feldspar occurs with interstitial nepheline and pyroxene. The other carries nepheline as euhedral primary crystals. In both types antiperthite forms short prisms. Aegirine-augite, analcime and sodalite (as pseudomorphs after nepheline) occur as interstitial grains. Biotite, magnetite and apatite are usually enclosed by other minerals while sphene and zicron are sporadically present.

The Coarse-grained Nepheline Syenite

This unit occurs as an irregularly shape body around the core nepheline syenite of which it carries xenoliths. It was the last ring unit to be emplaced with only the radial dykes to follow. Its feldspar phenocrysts

exhibit a marked parallelism resulting in a characteristic flow structure with an apparent vertical arrangement. The phenocryst nepheline is rather fresh although the groundmass phase is often replaced by sodalite and sometimes by calcite. Aegirine-augite is the main mafic mineral, amphibole and biotite are scarce whereas iron ore and apatite occur as aggregates with or enclosed by most of the other mafic minerals.

The Sodalite Syenite

Numerous xenoliths of sodalite syenite are grouped together in two elongated areas on the southwestern flank of the complex. The one group occurs in the grey nepheline syenite ring whereas the other transects the contact between this and the white nepheline syenite unit. The xenoliths are usually rounded with sharp contacts and range in size from a few centimetres to a couple of square metres. Their vertical distribution is unknown.

Variation in grain size and mineral proportions is a conspicuous feature of this rock type. The xenoliths usually consist of perthite phenocrysts set in a groundmass of feldspar sodalite, pyroxene, amphibole, iron ore and accessory minerals. Nepheline is scarce in the groundmass and seems to be replaced by a zeolite. This rock type carries the highest concentration of sodalite, sphene and zircon of all the syenites - a fact which suggests the accumulation of volatiles during its formation. Verwoerd found the origin of this rock difficult to explain because of (1) its very localized distribution, (2) its fine-grained groundmass which indicated rapid cooling and (3) its occurrence as xenoliths in the white and grey nepheline syenite which makes it the second oldest rock type present. Its age relationship therefore contrasts with its high volatile content.

Nepheline syenite dykes

The emplacement of two sets of radial dykes, a light grey and a black variety, concluded the magmatic activity at Etaneno. These dykes, which show vertical dips and sharp contacts, range in strike length from a few to 300 metres and in width from one to three metres.

The grey type carries abundant nepheline and tabular feldspar pheno= crysts set in a medium to fine-grained groundmass of feldspar, nepheline and mafic minerals. The black variety is less abundant and exhibits a more pronounced porphyritic texture. They carry lesser amounts of nepheline together with tabular feldspar in a dense very fine-grained blackish groundmass which consists mainly of aegirine-augite and hasting= site. Biotite and olivine are present in some dykes while apatite, sphene and zircon are scarce.

A few isolated bodies with apparent cross-cutting relationships occur on the northern and southern slopes of the mountain. They carry xenoliths of the various nepheline syenite rock types set in a matrix which resembles that of the core nepheline syenite.

1.2.5 The Carbonatite Complexes

1.2.5.1 Kalkfeld

This complex is situated about eight kilometres from the village of Kalkfeld. It is nearly circular in plan (Fig. 5) and is surrounded by a conspicuous range of hills consisting of fenitized granite. Van Zijl (1962) recognized the following rock units.

Granite
Syenite
Nepheline syenite
Granite and syenite fenites
Carbonatite and metasomatic feldspar rock
Small nepheline syenite plugs
Iron ore
Tinguaite dykes
Dolerite dykes

New chemical data (Chapter 2) support the idea that the granitic rocks do not belong to the complex but to the Salem granite suite as originally proposed by Verwoerd (1967). The syenite forms an incomplete ring inside the granite envelope. Like the granite it has been intensely fenitized. These fenitic rocks differ from those at Okorusu, where large areas have been transformed into massive pyroxenite, but is similar to fenitized aureoles of complexes such as Fen, Spitzkop, etc. A detailed description of these rocks is given by Van Zijl (op.cit.) and in Chapter 4. Nepheline syenite occurs as scattered outcrops in a zone between the carbonatite and the surrounding syenite hills. The carbonatite plug covers an oval area of nearly 1,5 sq kilometres near the centre of the complex and consists mainly of a grey-weathering equigranular sövite with micaceous and apatite-rich zones (Fig. 6). Its mineralogical composition varies considerably with calcite the dominant carbonate and limonite, apatite, barite and monazite in minor amounts. Accessories such as chlorite, albite, ankerite, pyrochlore, pyrite and quartz are usually associated with apatite.

Syenite porphyry dykes up to three metres in thickness and consisting of albite phenocrysts set in a fine-grained matrix of orthoclase, limonite and accessory calcite and zircon, are to be found near the central hills.

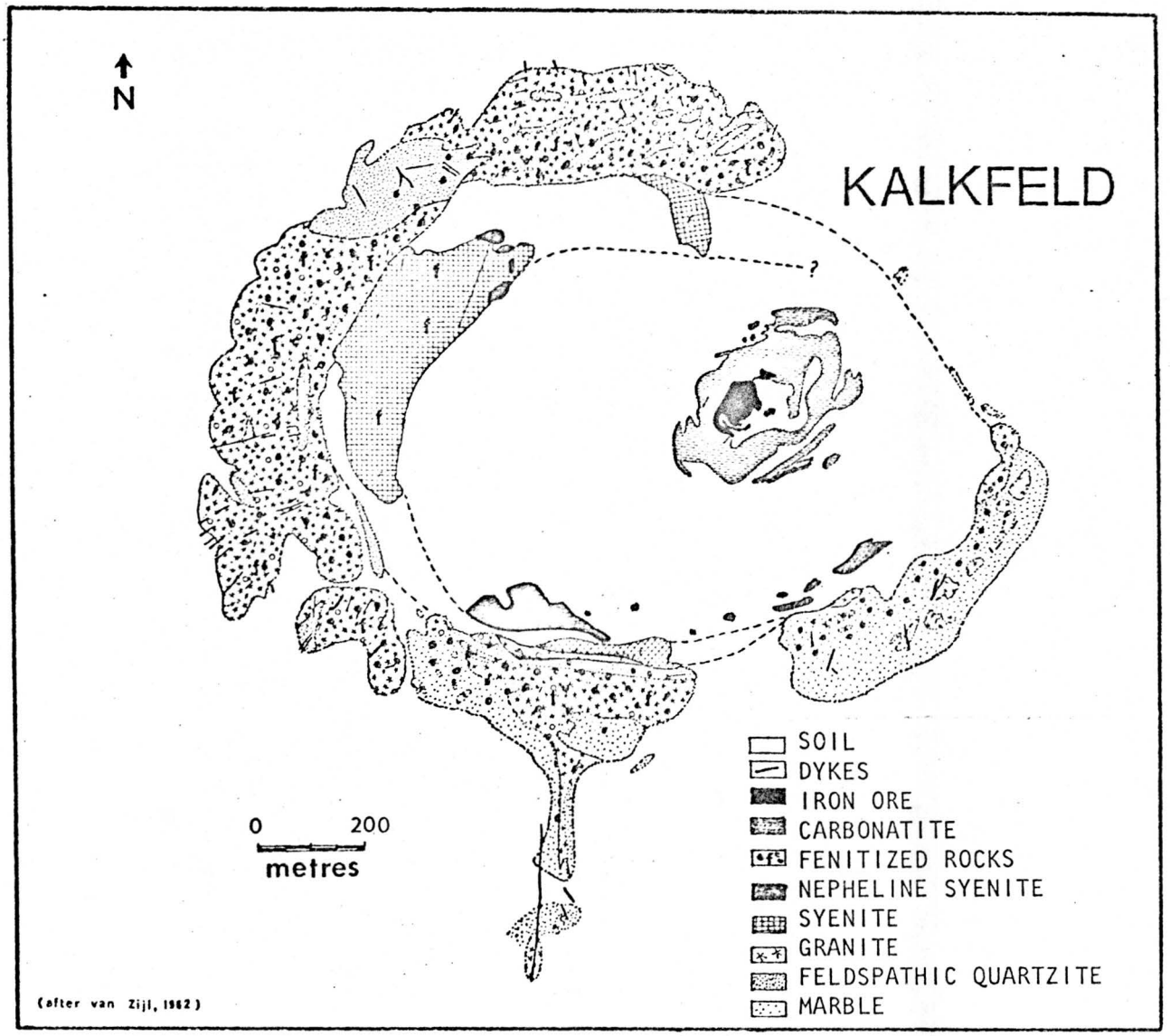


Fig. 5: Geological map of the Kalkfeld carbonatite complex.

A massive brown-red plug of oxidized iron ore, analogous to occurrences at Fen and Chilwa Island, builds the central hills at Kalkfeld. Agglomerate carrying small, well-rounded fragments of syenite and trachyte, with a pisolitic character at times, occurs along the northern and western contacts of the iron deposit. Elongated bodies of a fine-grained pinkish syenite occur as xenoliths in the carbonatite. Two nepheline syenite plugs are situated in the carbonatite mass near these xenolith occurrences. The presence of a well-defined chill zone indicates that these rocks are of post carbonatite age.

Olivine dolerite dykes are relatively scarce and occur mainly as a NNE striking swarm near the iron deposit. Highly altered dyke rocks consisting mainly of hydrobiotite and calcite with reddish K-feldspar as an accessory mineral can be found within the carbonatite.

1.2.5.2 Osongombo

The occurrence of an iron-rich beforsite plug at Osongombo is not only the smallest exposed carbonatite complex of the Damaraland alkaline province but the sole one without associated siliceous rocks. Verwoerd (1967) mapped this occurrence (Fig. 7) and described it as a diatreme representing the uppermost part of his proposed model for the Kalkfeld group of carbonatite complexes.

An iron ore deposit is situated in the centre of the beforsite plug. Although much smaller in size it is remarkably similar in mineralogy to those at Kalkfeld and Ondurakorume.

1.2.5.3 Ondurakorume

During the last decade the Ondurakorume carbonatite, first described by Verwoerd (1967) attracted the attention of mining companies as a result of its associated apatite and rare earth mineralization. During 1965 Verwoerd conducted a radiometric survey of the complex while C.A. Key prepared a geological map, subsequently revised by R.G. Collins. Neither the work by Key nor Collins has been published but the present author was fortunate in obtaining access to the drill cores and permission to use Collins' map (Fig. 8).

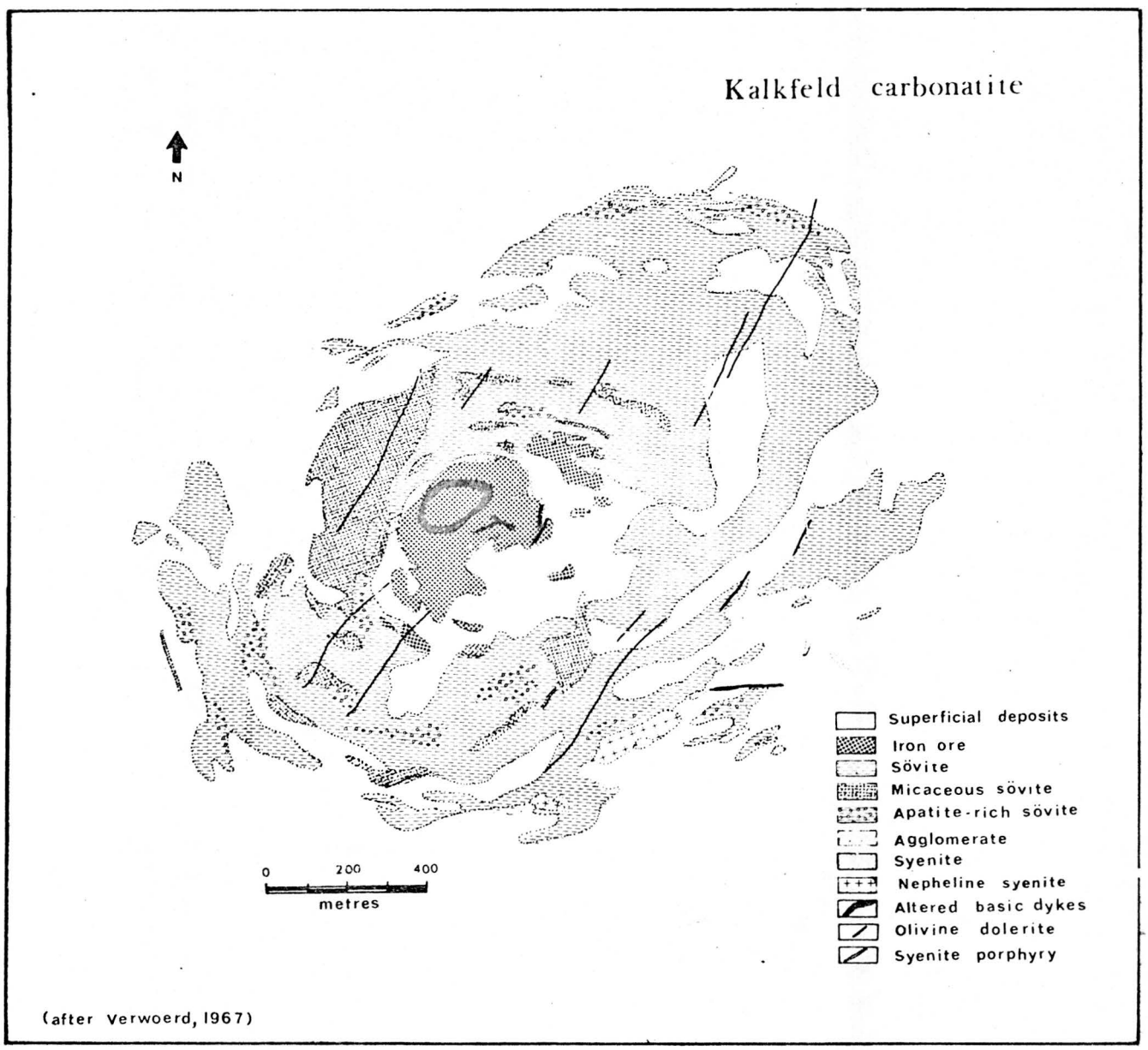


Fig. 6: Geological map of the Kalkfeld carbonatite.

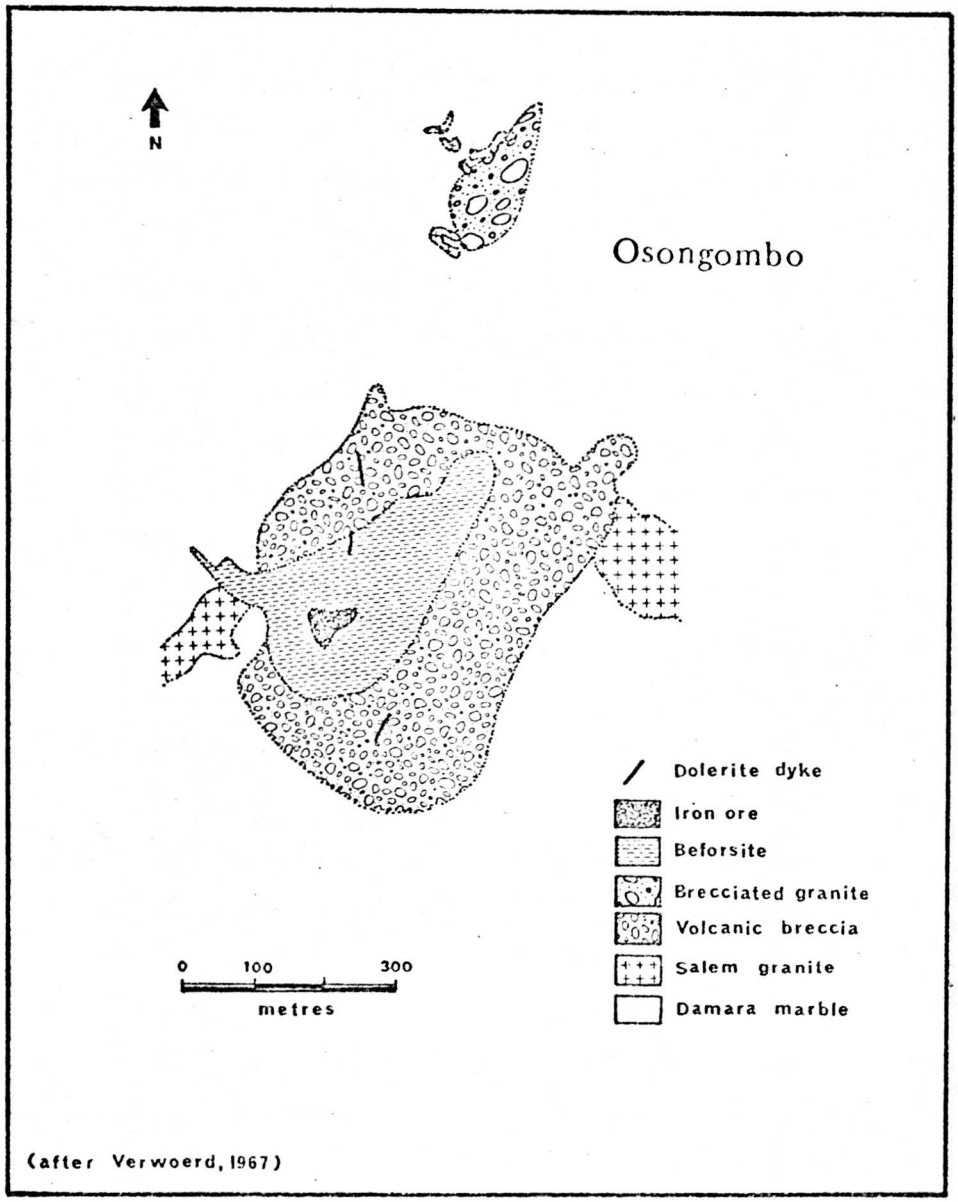


Fig. 7: Geological map of the Osongombo carbonatite diatreme.

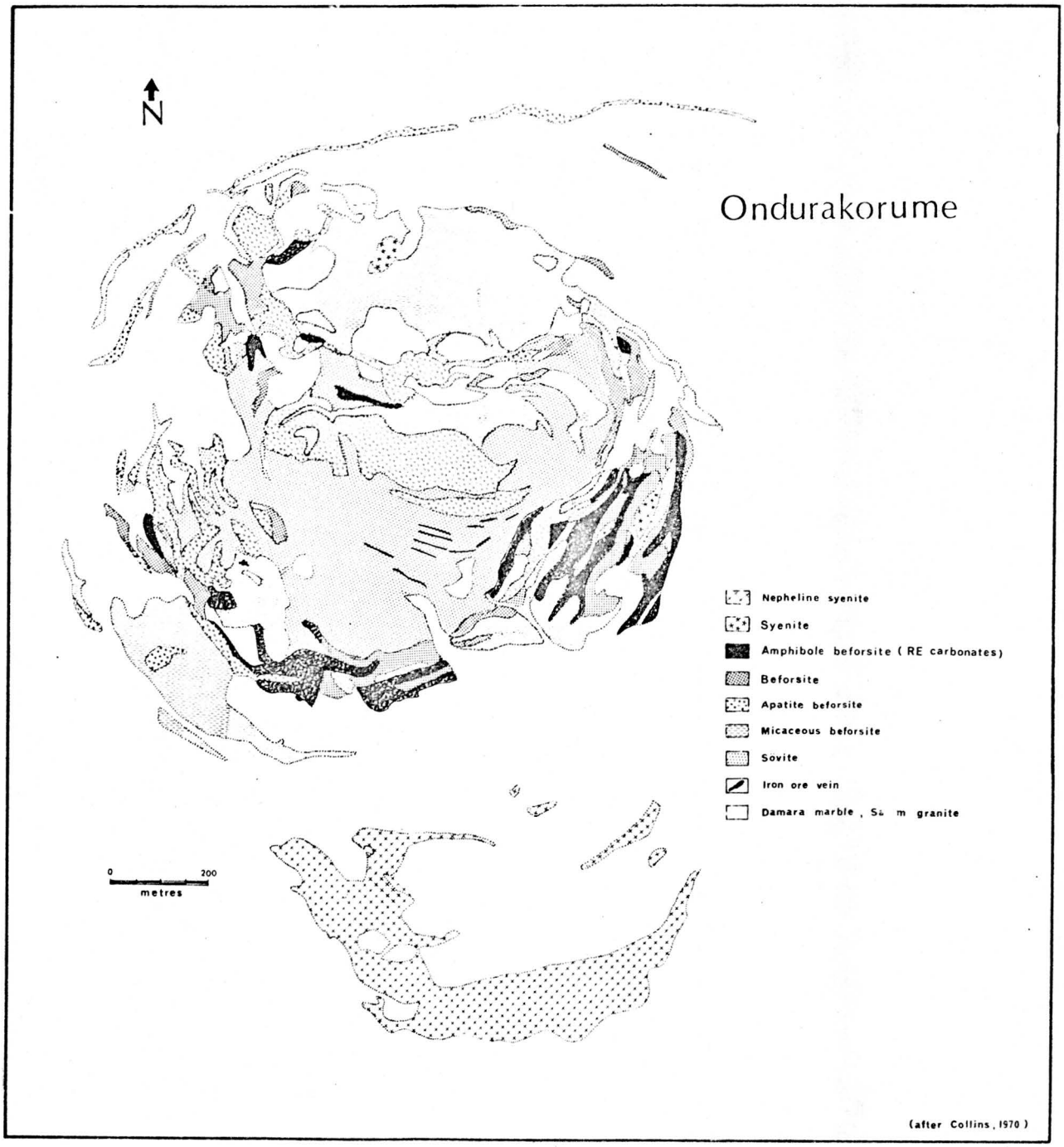


Fig. 8: Geological map of the Ondurakorume carbonatite complex.

A sequence of marble, quartzite, graywacke and schists of the Damara Super= group as well as Salem granite build the country around Ondurakorume. Ex= tensive shattering and fenitization can be seen in the more competent members of this sequence.

A dark coloured micaceous sövite forms a central plug around which the other carbonatite intrusions were emplaced. The micaceous sövite consists of cal= cite and dolomite with fine-grained biotite which is invariably altered to dark green chlorite and yellowish vermiculite. A characteristic feature of this unit is the appearance of "pisolitic structures"(3mm - 1cm in size) made up of hydrobiotite, calcite and apatite.

The second member of the carbonatite suite is massive white sövite which crops out as separate bodies arranged in a near circular pattern. Plugs, lenses and ring dykes of brown-weathering beforsite carrying variable amounts of cal= cium, magnesium and iron carbonates were intruded next. Apatite-rich zones within these intrusives have been investigated for their economic significance.

The youngest intrusive carbonate phase resulted in a series of relatively small lenses and ring dykes of dark grey-blue beforsite. These rocks are heavily impregnated with fibrous blue riebeckite while magnetite, pyrochlore, monazite and ancylite are the most common accessory minerals. Rare earth carbonate minerals may occur in concentrations up to 10 per cent.

Dyke-like bodies of oxidized iron ore occur in the micaceous beforsite and in the white sövite along the southeastern flank of the hill.

Small bodies of highly altered syenite occur sporadically within the carbonatite and a sickle shaped outcrop of nepheline syenite occurs on the southern foothill of the complex. A set of altered olivine dolerite dykes cut accross the com= plex in a northern direction.

1.2.5.4 Okorusu

Van Zijl (1962) described the geology of this complex in detail. He suggested that it was formed by several confocal intrusions of alkaline magmas followed by

brecciation and fenitization of the wallrocks and the emplacement of carbo=natitic plugs along its southern contact. He recognized the following se=quence of rock types:

Fluorspar deposits
Iron ore deposits
Limonite-feldspar-carbonate metasomatic rock
Pyroxene fenite
Carbonatite
Tinguaite dykes and plugs
Fine-grained dark nepheline syenite
Coarse-grained white nepheline syenite and urtite
Early syenite
Hortonolite monzonite

The monzonitic rocks occur as xenoliths in the coarse syenite of the central hills. Microperthite is the dominant mineral while plagioclase forms con=spicuous laths up to 3 centimetres in length.

Two varieties of syenite are present. The oldest, which can be identified by its coarser grain-size and more pronounced foliation forms the outermost ring. The second type forms a narrow zone up to 300 metres wide around the central coarse nepheline syenite and displays no visible foliation. Both these syenites consist of perthite and pyroxene with minor amounts of plagioclase, hornblende, biotite and accessory zircon, apatite, magnetite, calcite and haüyne and have not been affected by metasomatism to the same extent as those of Kalkfeld.

A plug of extremely coarse syenite and nepheline syenite grading into urtite occurs near the centre of the complex. It appears to be intrusive into the earlier syenites. Isolated bodies of dark fine-grained nepheline syenite which sometimes may approach an ijolitic composition occur in the southwestern part of the complex. Rocks described as nephelinites by Van Zijl also occur in this area. They are fine-grained and contain round as well as irregular globules which consist mainly of calcite, analcite, phlogopite and Fe-oxides. Van Zijl regarded these structures as amygdales. The occurrence of volcanic rocks at this level of erosion is suspicious and an alternative interpretation of their origin is given in Chapter 7.

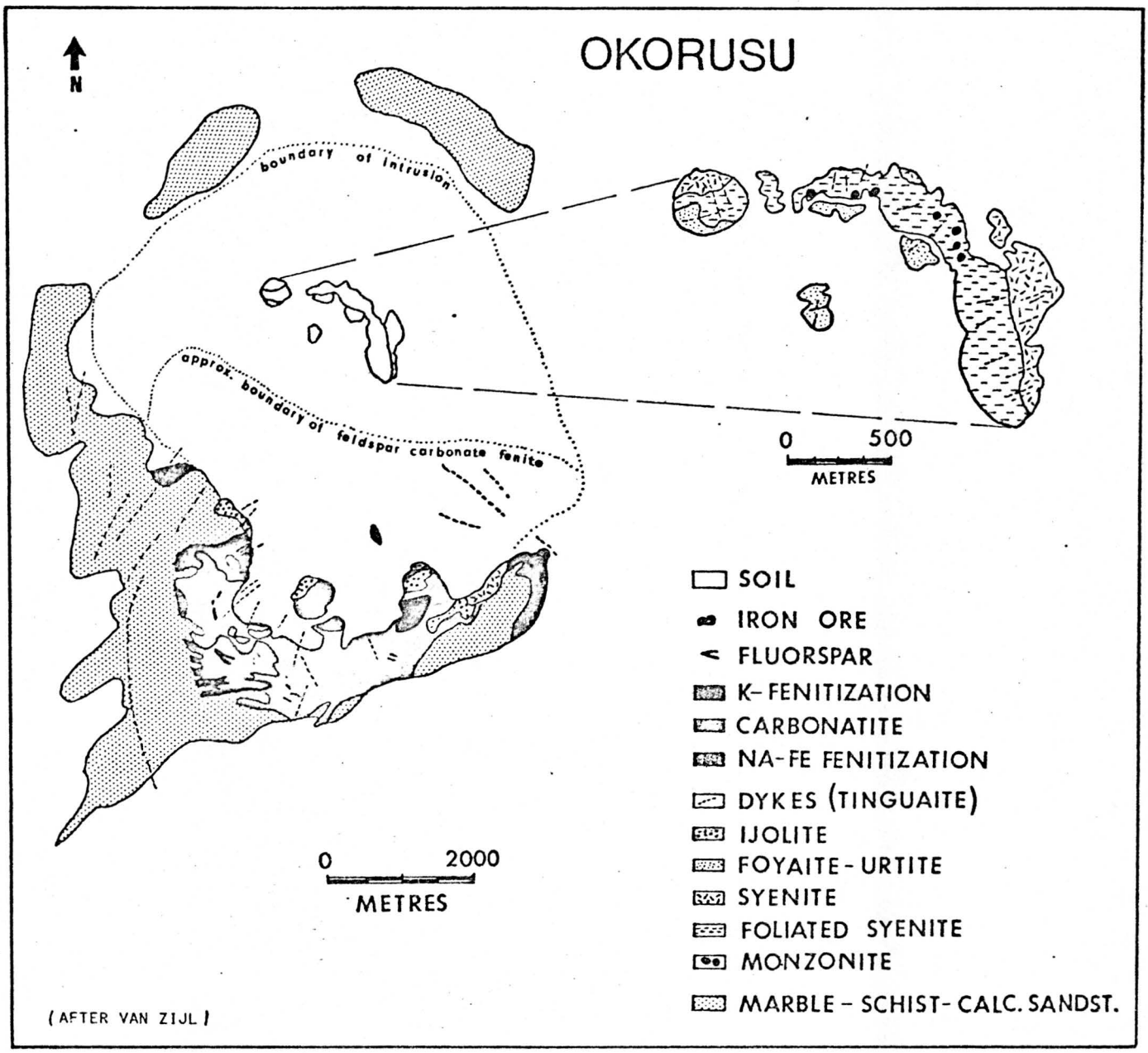


Fig. 9: Geological map of the Okorusu carbonatite complex.

Carbonatite plugs containing more than 90 per cent calcite with apatite, quartz and feldspar as accessory minerals, occur in the flats north of the Okorusu hills. A recent visit to the complex revealed that these rocks occur over an area much larger than previously thought. The presence of a carbonatite agglomerate has also been established.

Two major episodes of metasomatism resulted in a massive calcite-bearing pyroxene fenite which was subsequently altered by extensive brecciation and feldspathization. These phenomena are described in Chapter 4. One of the world's largest fluorite deposits occurs in the form of drusy fluorite-quartz veins in the limestone wallrocks along the southern contact. Iron ore lenses with no apparent economic potential occur in the alkaline as well as carbonatitic units. Dark fine-grained tinguaitic rocks occur as radial dykes and as plugs within the complex and its adjacent wallrocks while a series of small lamprophyre plugs are scattered all over the complex.

CONTENTS

2 THE ALKALINE ROCKS

2.1 MAJOR ELEMENT VARIATION

2.1.1 Introduction

Chemical analyses of the more important rock types of the Kalkfeld and Okorusu complexes are given by Van Zijl (1962) and Verwoerd (1967). In this study 65 new chemical analyses were obtained by X-ray fluorescence and wet chemical methods. Changes and improvements that were necessary in the existing techniques are described in the Appendix, together with the analytical results, sample numbers, localities and other relevant information.

The chemical variation among the rocks of an igneous province or those of a specific intrusive complex can be illustrated by diagrams in which the OXIDES are plotted versus an INDEX (representing magmatic evolution). The differentiation index (D.I.), proposed by Thornton and Tuttle (1960), which is simply the weight percentage of the CIPW normative components (q+ab+or+ne+lc+kp), is preferred in this study because;

(i) the D.I. value is independent of silica saturation,

(ii) it has a satisfying thermodynamic basis (Carmichael, et al., 1974) and

(iii) being a widely used index, it facilitates comparison with analogous complexes elsewhere.

Chayes and Yoder (1971) argued that the CIPW norm is invalid for silica-undersaturated peralkaline igneous rocks. The Le Bas norm, specially designed for the study of silica-undersaturated rocks has, unfortunately, not escaped several

anomalies with respect to alkaline rocks that are also found in the CIPW norm. However, the Le Bas rules do improve the correlation between normative and modal constituents, especially for alkaline ultramafic rocks. As such rock types are virtually absent in the Damaraland province and because the Differentiation Index requires the use of CIPW normative constituents, the calculation of Le Bas norms was considered an unnecessary exercise.

Triangular diagrams are constructed to show the mutual relationship between any three components or combinations of components. In this study the (Na_2O+K_2O) - $(FeO+Fe_2O_3)$ - MgO and the Qz-Ne-Kp triangles were found to be useful diagrams whereby differentiation trends could be depicted. The SiO_2-Al_2O_3-(Na_2O+K_2O) diagram, devised by Bailey and MacDonald (1969) to test for feldspar fractionation, was also used.

2.1.2 Kalkfeld

The variation of the major elements with respect to the Thornton-Tuttle differentiation index of the various rocks of this complex is presented in Fig. 10. The K_2O, Al_2O_3, Fe_2O_3 and TiO_2 values would seem to indicate that the granite rocks do not belong to the trends exhibited by the alkaline rocks. This feature supports the idea of Verwoerd (1967) that these rocks belong to the Salem granite suite and not to the alkaline complex. The dolerite dykes seem to belong to a different phase of magmatic activity also. The alkaline rocks display an increase in SiO_2, Al_2O_3, K_2O and a decrease in Na_2O, CaO, MgO and total Fe_2O_3 with differentiation. MnO show no particular regularity. These trends, except that of Na_2O, can be considered normal for alkaline rocks which developed through crystallization differentiation.

2.1.3 Okorusu

In this case the variation in most oxide abundances with D.I. (Fig. 11) is similar to that displayed by the Kalkfeld rocks. However, much less scatter is observed in the Okorusu trends. This could mean that some of the rocks from Kalkfeld were affected by post-crystallization processes causing their deviation from the regular trends which normally result from differentiation, whereas the Okorusu rocks were not so affected. This is supported by the petrography of the Kalkfeld syenites which do not have a typical igneous texture or appearance while all the Okorusu rocks exhibit such textures.

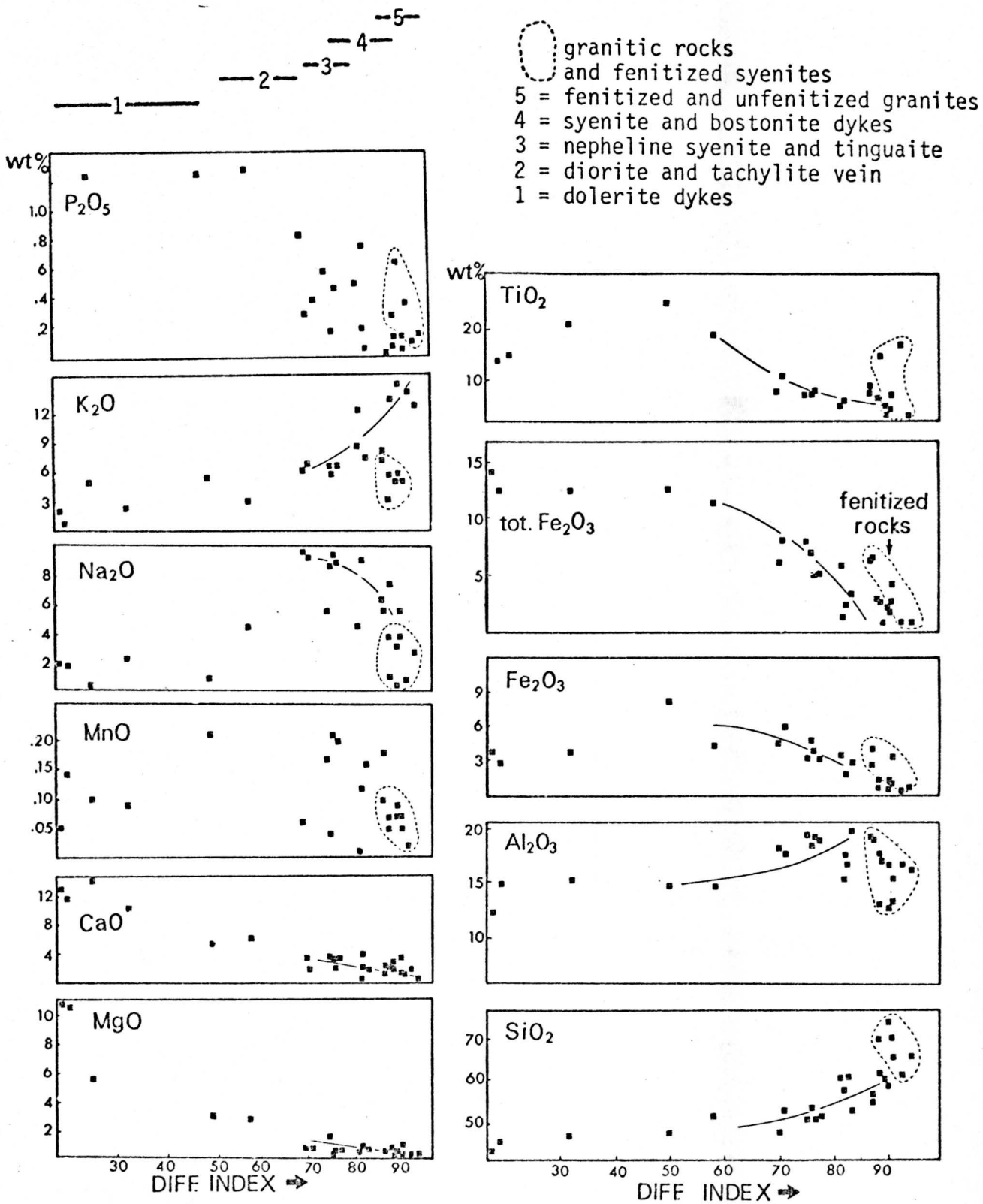


Fig. 10: Major element variation in rocks from the Kalkfeld complex.

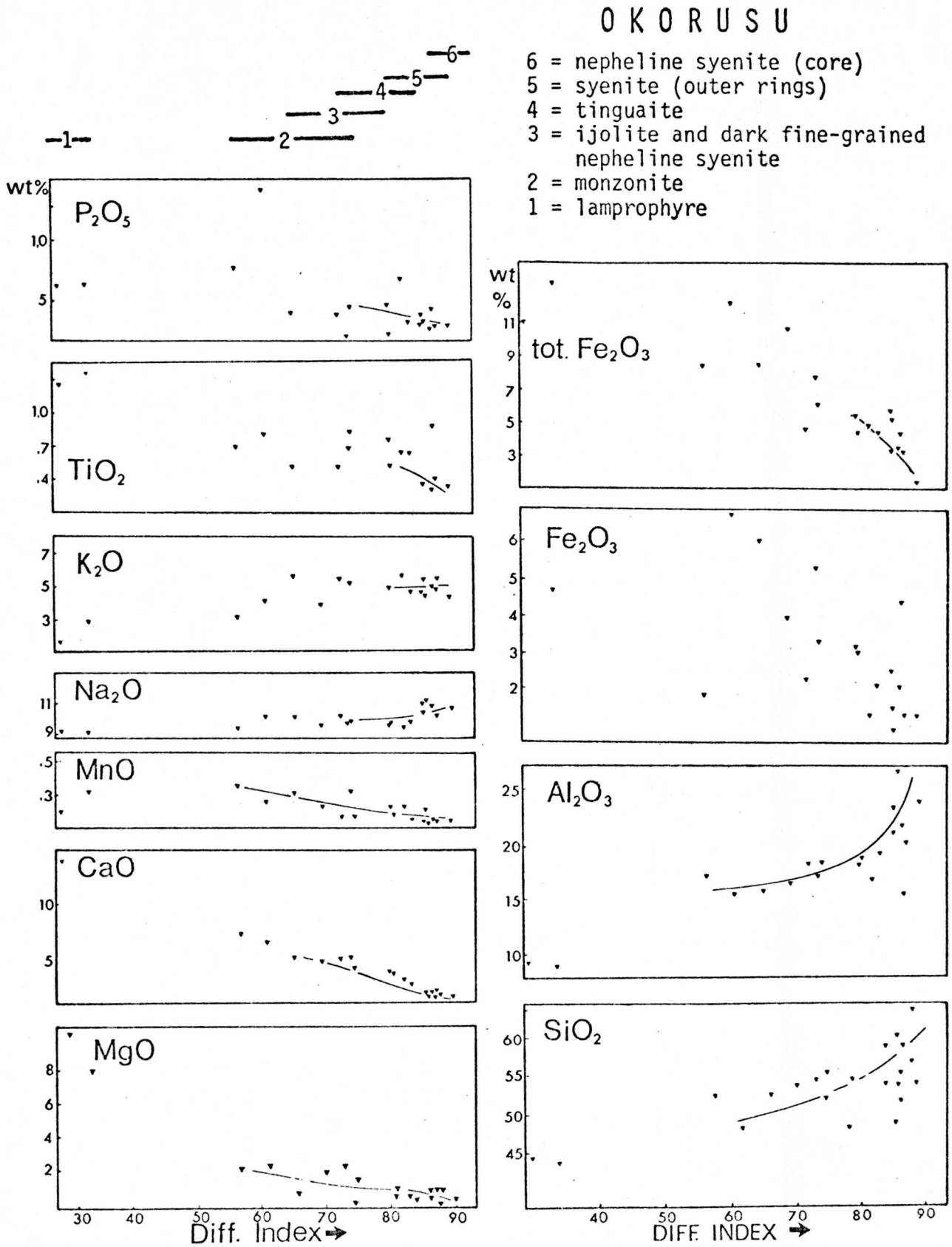


Fig. 11: Major element variation in the rocks from the Okorusu complex.

The Okorusu rocks show an increase in Na_2O with differentiation and very little variation in K_2O content. In contrast the Kalkfeld rocks seem to exhibit a sharp increase in K_2O and a decrease in Na_2O with differentiation. This might also be interpreted as the result of post-crystallization K-enrichment. The relative decrease in Na_2O with increase in D.I. would thus be explained.

2.1.4 Etaneno

The Etaneno Complex is situated close to the carbonatite-bearing alkaline complexes of Osongombo, Kalkfeld and Ondurakorume (Fig. 1) and this suggests that their development may have stemmed from a single parental magma situated in depth.

No signs of extensive *in situ* differentiation are present in any of the intrusive units at Etaneno. The bulk composition of rocks from these units is thus considered to represent the initial composition of the magma of each intrusive phase. On a D.I. variation diagram (Fig. 12) these rocks do not plot in the order of crystallization deduced from field and petrographic evidence. This is not very surprising considering the small variation in their D.I. values. Nevertheless, a significant increase in K_2O and Na_2O and a decrease in CaO, TiO_2 and total Fe_2O_3 seems to be associated with an increase in D.I.

2.1.5 Alkali-alumina relationships

The difference in the behaviour of Na and Al in the main alkaline intrusions of the Kalkfeld, Etaneno and Okorusu complexes is well illustrated in plots of the molecular equivalent ratio Na_2O/Al_2O_3 against the D.I. of the rocks concerned. It was already shown that the dolerite and bostonite dykes do not participate in the trends shown by the major elements. These rocks were therefore not used in the construction of Fig. 13.

It can be seen (Fig. 13) that the rocks from Kalkfeld and Okorusu define a generally decreasing trend with differentiation whereas those from Etaneno show an increase in this ratio with differentiation. It is tentatively suggested that a decreasing trend reflects Na_2O loss from a crystallizing melt. This

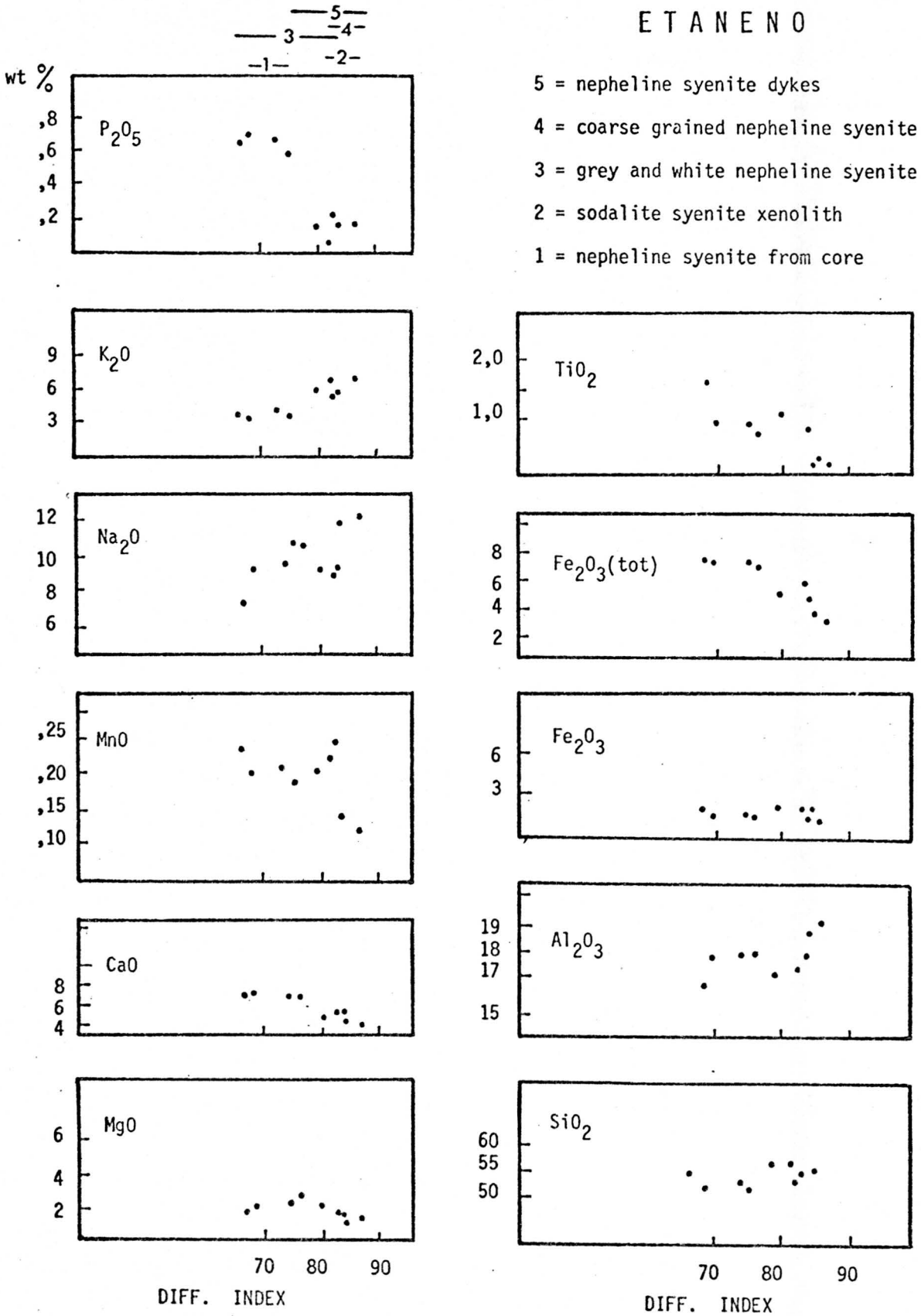


Fig. 12: Major element variation in the rocks from the Etaneno complex.

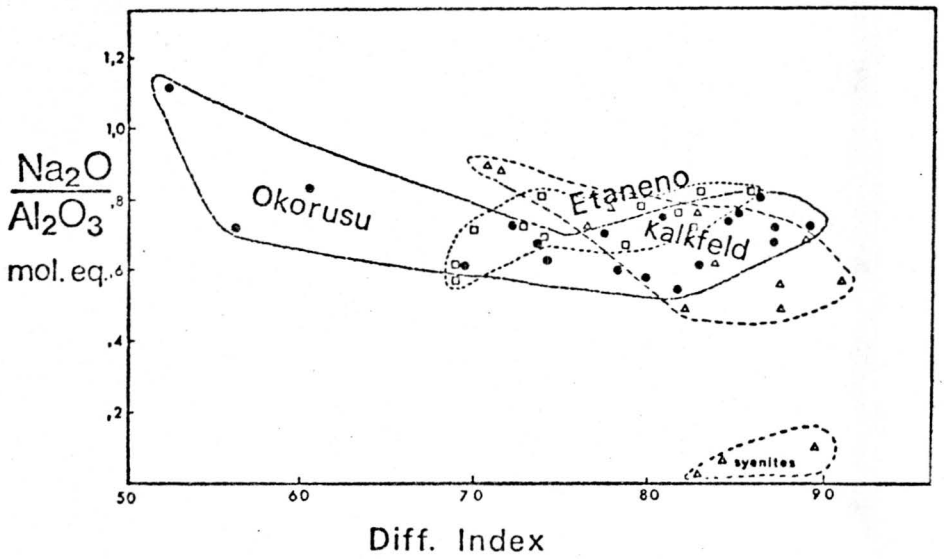


Fig. 13: Variation in the Na_2O/Al_2O_3 mol. eq. ratio of alkaline rocks from Okorusu, Kalkfeld and Etaneno. The decreasing trends might reflect sodium loss during differentiation.

implies that the Etaneno liquids and the later melts at Okorusu did not lose any sodium during their crystallization and could therefore not give rise to sodium fenitization.

The effect of sodium loss on the alkaline rocks of Okorusu and Kalkfeld can be correlated with both the modal and normative compositions of these rocks. In the calculation of the CIPW norm an increase in alkalis will cause the conversion of mt to ac and ab to ne with excess sodium expressed as ns. A decrease in sodium would thus have the reverse effect causing the magma to become mt normative.

It is shown in Fig. 14 that the variation in Na_2O content of the Okorusu and Kalkfeld rocks is clearly reflected by the amounts of mt in their CIPW norms. A significant feature of this plot is the fact that the syenites and nepheline syenites of Okorusu are magnetite normative with no ns in their norms. On the other hand similar rocks from Kalkfeld are ns normative. A plot of Na_2O against model content of black opaque minerals of the rocks under consideration (Fig. 15) shows an increase in magnetite with decreasing Na_2O content. A similar feature is described by Melchior Larsen and Steenfelt (1974) for an iron-rich peralkaline phonolite dyke from the Gardar Province. These authors show that a loss in Na_2O

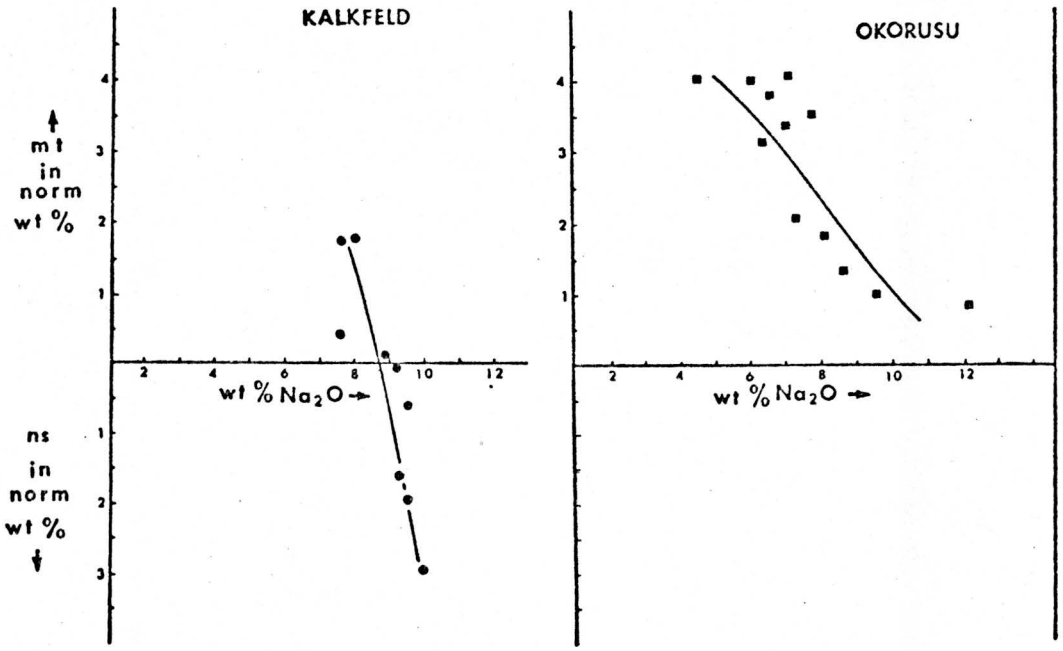


Fig. 14: Plots showing the correlation of the Na_2O content of the nepheline syenites and ijolites of the Kalkfeld and Okorusu complexes with their normative amounts of magnetite and sodium silicate.

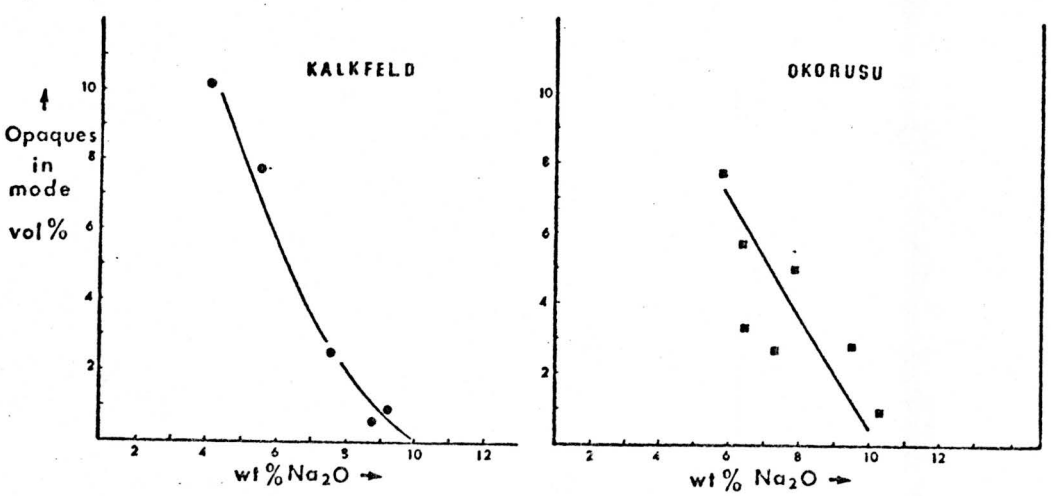


Fig. 15: Plots showing a decrease in opaques with increase in Na_2O content in alkaline rocks from Okorusu and Kalkfeld. (data taken from Van Zijl, 1962).

will drive the composition of a liquid in the Na_2O-Al_2O_3-Fe_2O_3-SiO_2 system away from the phase boundary acmite-nepheline-albite into the oxide stability field with a resultant increase in the precipitation of iron oxides.

It thus seems likely that the large amounts of sodium which must have been lost from the Okorusu magma during the first stage of fenitization caused extensive extraction of iron from the magma by the precipitation of magnetite. This process did not operate to the same extent at Kalkfeld where the magmas remained ns normative. In this case Fe was probably stabilized in the melt so that no extensive removal of Fe (through the precipitation of magnetite) occurred during the crystallization of the early alkaline magmas. This could be an explanation for the relative abundance of Fe in the carbonatite and associated hydrothermal fluid which developed from these melts.

Melchior Larsen and Steenfelt (1974) proposed that the loss of alkalies from the eastern part of the Gardar dyke was due to a higher temperature environment under which this section of the dyke crystallized. Such an explanation does not seem applicable to the Damaraland intrusions and it is thought that in this case the loss of sodium was a direct result of the highly alkaline character of the magma. The total alkali content of the rocks of both complexes exceeds their alumina content. It is thus probable that the amount of sodium that could not be accommodated by the crystallization of feldspar and/or nepheline was lost by volatilization as suggested by Kogarko (1974) during the crystallization of the ijolite/nepheline syenite magmas.

The anomalous position of the Kalkfeld syenites in Fig. 13 again supports the suggestion that these rocks were subjected to metasomatic changes after their crystallization.

2.2 TRACE ELEMENTS

In all types of alkaline rocks the most typical trace elements are those of lithophilic character. Volatile elements may also play a significant role in alkali rock genesis, specially when these rocks are associated with carbonatites. The following trace elements were thus analized for : Sr, Ba, Rb, Zr, Ce, Y, La, Nd, Nb, F, Cl.

2.2.1 Strontium

Strontium substitutes for both Ca^{++} and K^{+} in mineral structures only when co=ordination conditions are satisfied. It thus replaces Ca in plagioclase but not in pyroxene (Taylor, 1965). The behaviour of Sr during fractionation of a magma may therefore become complex and may vary depending on the relative amounts of Ca-pyroxene and plagioclase that are removed (Berlin and Henderson, 1968; Korringa and Noble, 1971).

The rocks of the three alkaline complexes under consideration all show a marked decrease in Sr with differentiation (Fig. 16, 17 and 18). This is to be ex=pected in the case of feldspar fractionation because the distribution coeffi=cients (D_K) for sodic plagioclase and alkali feldspar vary between 3 and 4 (Berlin and Henderson, op.cit.). Fractionation of these phases thus seems to have played a role in the formation of these rocks.

Strontium usually shows a sympathetic relationship with the Ca content of igneous rocks. However, rocks from the Etaneno complex only, show such a relationship (Fig. 19). Anomalous values are to be expected in rocks from carbonatite-bearing alkaline complexes if liquid immiscibility, fenitization and complex crystal fractionation processes (as proposed in Chapter 7) were operative during their formation. Such processes apparently did not play an important part at Etaneno.

2.2.2 Barium

Barium may substitute for K^{+} in alkali feldspar and biotite and for Ca^{++} in plagioclase, pyroxenes and amphiboles. The former substitution is more impor=tant and accounts for the relatively high Ba content of these minerals (Puchelt, 1971). Various authors have studied the distribution of Ba between phenocrysts and melts for a number of different minerals in different rock types. Distri=bution coefficients (D) were found to be generally higher than 1,0 for K-feldspar and biotite whereas all other minerals have D values less then unity (Philpotts and Schnetzler, 1970). According to Berlin and Henderson (1969) the data re=ported in the literature range between the following limits:

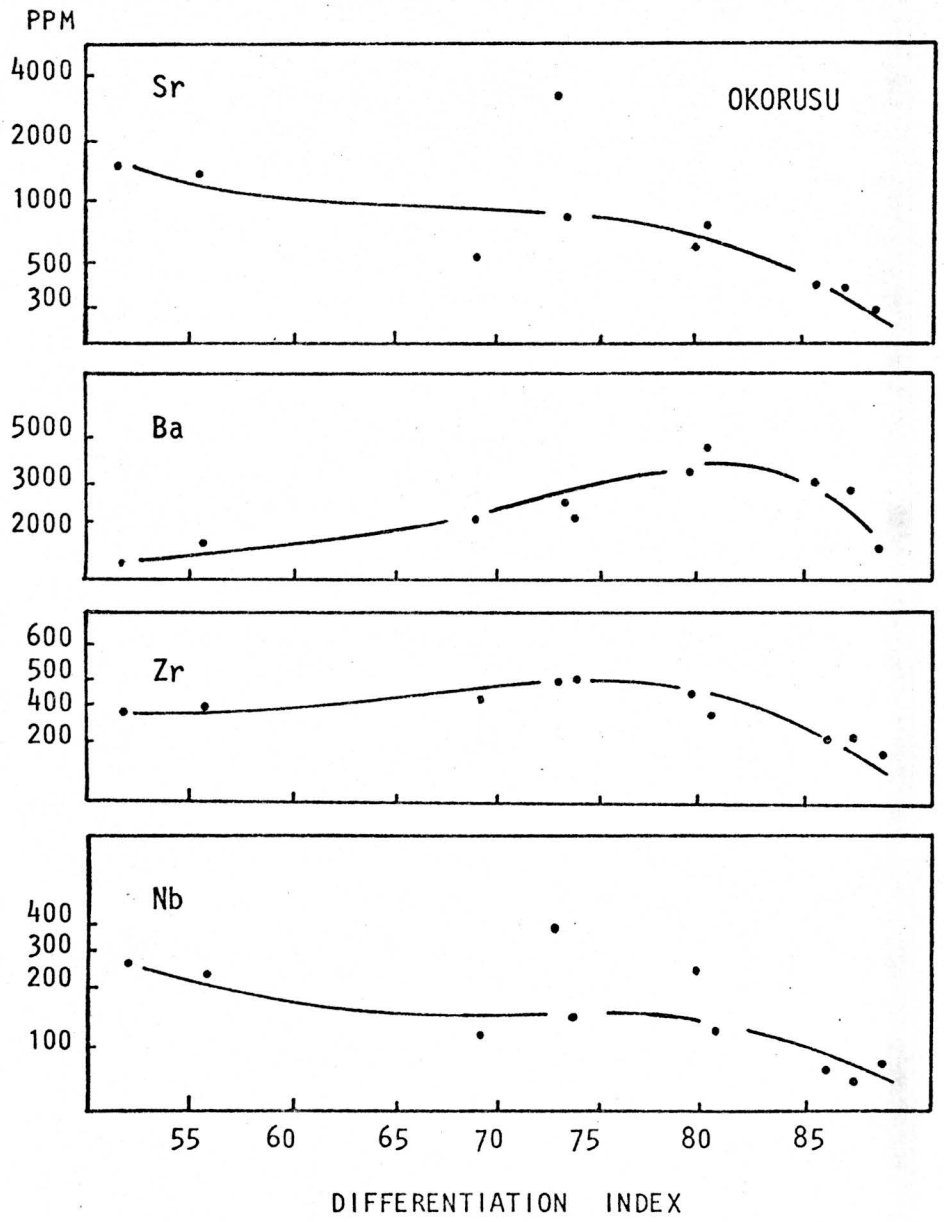


Fig. 16: Trace element variation in the alkaline rocks from Okorusu.

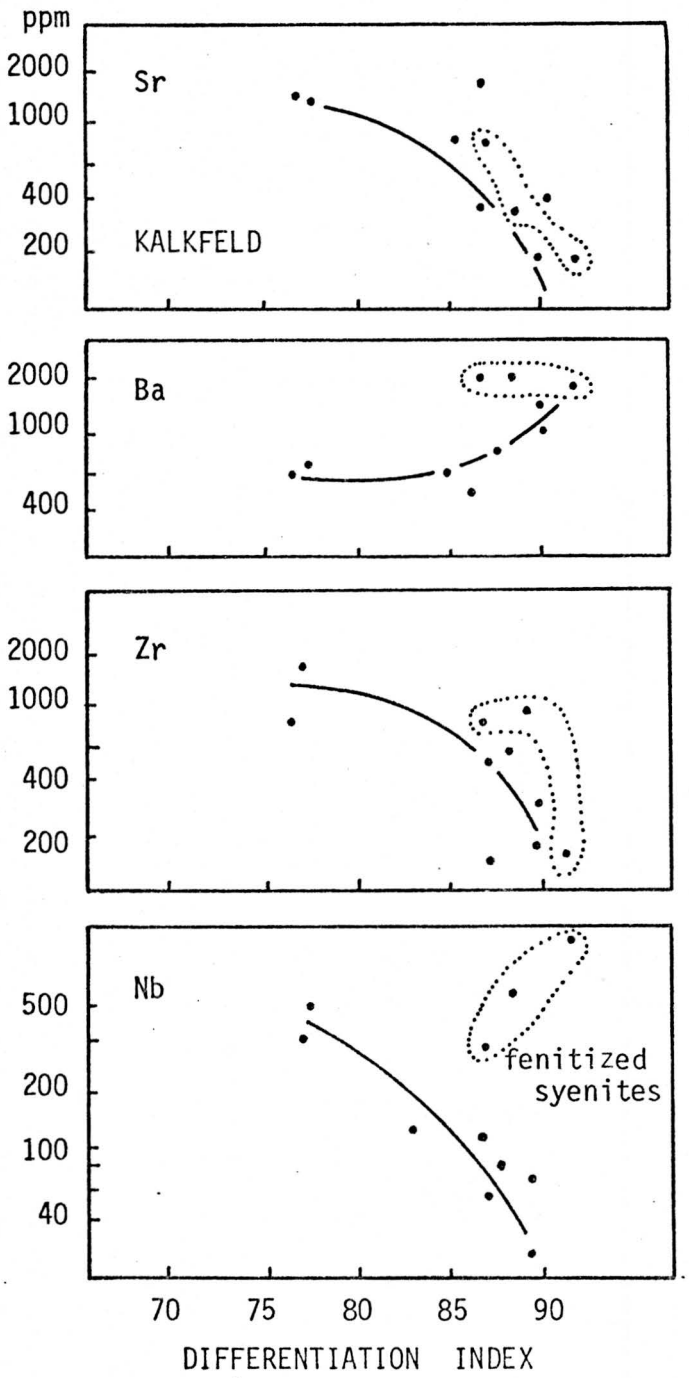


Fig. 17: Trace element variation in the alkaline rocks from Kalkfeld.

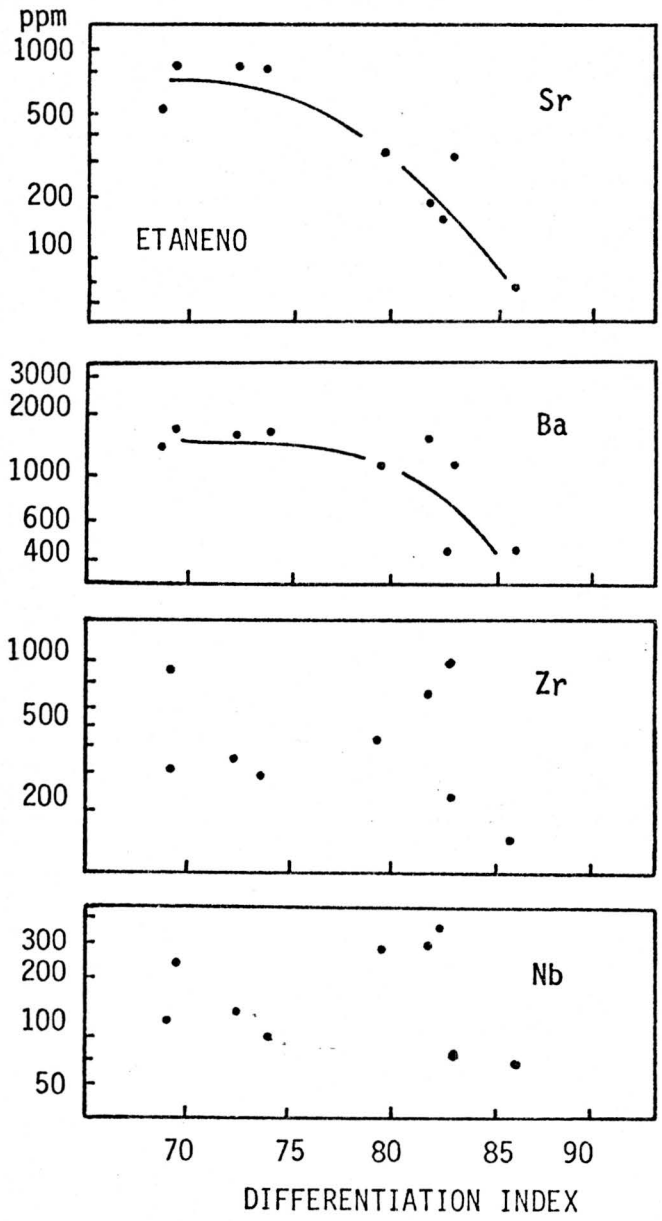


Fig. 18: Trace element variation in the nepheline syenites from Etaneno.

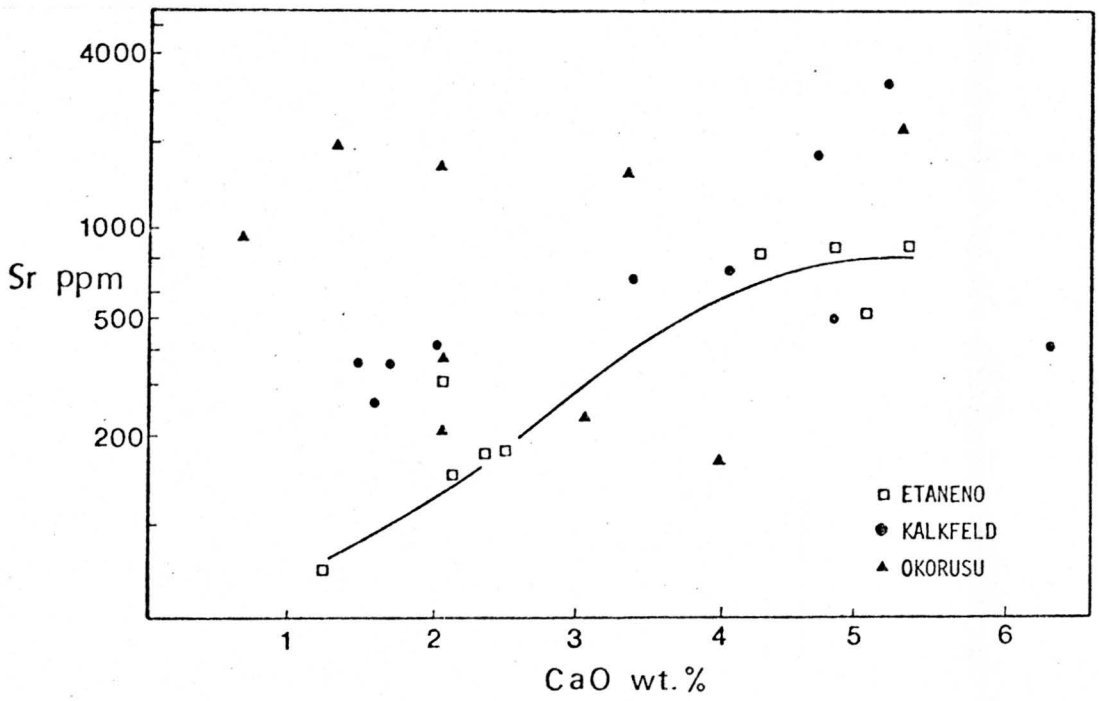


Fig. 19: A plot of Sr(ppm) versus CaO(wt%) of the alkaline rocks from the Kalkfeld, Okorusu and Etaneno complexes. Those from Etaneno only show a covariant relationshp.

Na-plagioclase	D = 0,72 - 1,09
Sanidine	D = 1,17 - 8,95
Biotite	D = 1,6 - 15

These distribution coefficients account for the increase in Ba which usually occurs when basic magmas fractionate through intermediate to alkaline or gra= nitic compositions. However, fractionation of biotite and/or K-feldspar will decrease the Ba content in residual fluids. The distribution of Ba in the alkaline rocks of Etaneno and Okorusu display such a behaviour as the concentra= tion of this element tends to increase in the early differentiates but decreases sharply once K-feldspar becomes a major fractionating phase in the later intru= sives. An anomalous increase in Ba is displayed by the highly differentiated rocks of Kalkfeld. This suggests that feldspar fractionation was not the do= minant process in their development (nepheline probably fractionated in equal amounts) and that the presence of minerals with high D values, such as biotite, might be responsible for the increased Ba content of these rocks.

2.2.3 Rubidium

Rubidium is generally associated with K for which it readily substitutes in alkali feldspar and biotite. Alkaline rocks, of which the miaskitic types contain the highest Rb concentrations, are enriched in this element relative to most igneous rocks (except granites).

Shaw (1968) came to the conclusion that the K-Rb relation in igneous rocks can take one of three forms which he referred to as; the main trend (MT), the oceanic tholeiitic trend (OT) and the pegmatite-hydrothermal trend (PH). The igneous rocks of the Damaraland alkaline/carbonatite complexes clearly belong to the upper part of the main trend with their associated fenites falling towards the pegmatite-hydrothermal trend (Fig. 20). Shaw mentioned further that the important question, i.e. whether rocks belonging to the main trend display constant or decreasing K/Rb ratios with differentiation, remains controversial. In this respect the alkaline rocks of this study show that at the high-potassium end of the main trend, a decrease or increase in this ratio is possible (see next section). The complex mineralogy and the ubiquitous presence of volatiles in alkaline intrusions seem to be responsible for these notable differences in K/Rb trends.

2.2.4 Whole rock K/Rb ratios

Factors, ratios and coefficients are frequently used without definition in the literature and this hampers interpretation of geochemical data. The K/Rb ratio is one which is sometimes calculated as $K_2O/Rb \times 10^4$ or as $K/Rb \times 10^4$. In a summary of the statistical trends shown by this ratio Shaw (1968) encouraged the use of the latter alternative.

Despite numerous investigations, e.g. Gunn (1965), Erlank (1968) the significance of K/Rb ratios is not always apparent. Little success has been achieved in correlating K/Rb of intrusive or extrusive rocks with oceanic of continental environments or in distinguishing between parental or derivative magmas (Carmichael, et al., 1974, pp.74).

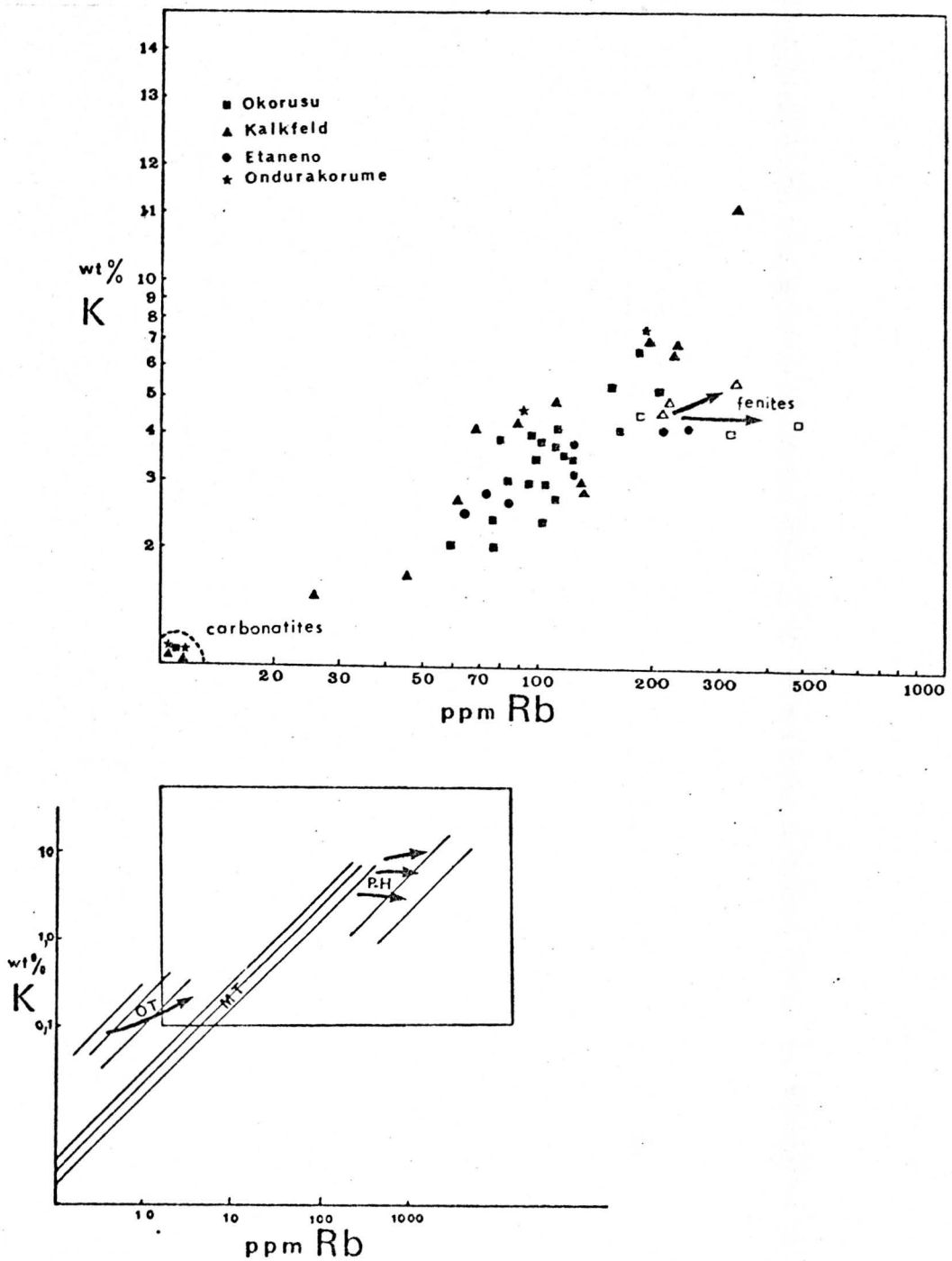


Fig. 20: The K/Rb fractionation trend of the alkaline/carbonatite complexes of Damaraland compared to trends suggested by Shaw (1968) for igneous rocks. (OT: oceanic tholeiitic basalts. MT: main trend. P-H: pegmatite hydrothermal trend).

The K/Rb ratios of the rocks from the complexes studied are of normal magnitudes and show fairly regular variations with differentiation indices - a feature which suggests that crystal fractionation controlled the composition of the magmas. Furthermore, the K/Rb ratios of the Kalkfeld group of complexes show a trend different from those of Okorusu, which, if any significance can be attached to this ratio, might indicate important differences in the development of the complexes.

2.2.4.1 Etaneno

The Etaneno alkaline rocks seem to display a trend, as reported previously for undersaturated alkaline rocks (Marsh, 1973), of decreasing K/Rb ratios with increase in differentiation (Fig. 21). Relative enrichment in Rb during differentiation was probably caused by the coprecipitation of feldspar and nepheline (as suggested in Chapter 7) both of which have D values less than unity (Dupuy, 1968).

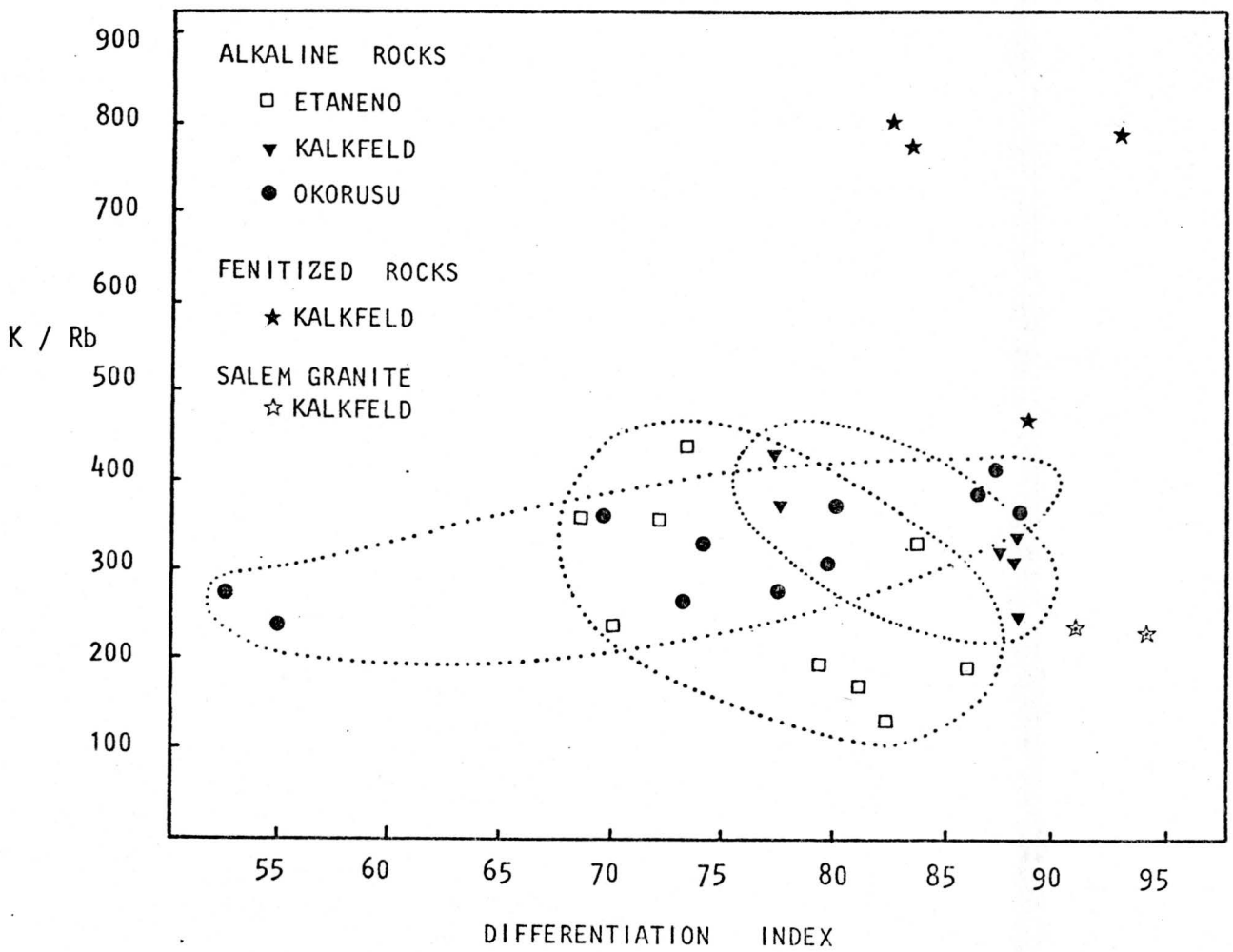


Fig. 21: K/Rb ratios of alkaline and metasomatic rocks from the Kalkfeld, Etaneno and Okorusu complexes.

2.2.4.2 Kalkfeld

The nepheline syenites of this complex show a K/Rb trend similar to that of Etaneno (Fig. 21), suggesting that the alkaline rocks from these complexes originated through similar fractionation processes. The fenitized and feldspathized syenite display anomalously high ratios which is a reflection of their increased K-content rather than a depletion in Rb. The granitic rocks have variable K/Rb ratios and apparently do not belong to the fractionation scheme of the alkaline rocks.

2.2.4.3 Okorusu

The Okorusu rocks in contrast with Kalkfeld and Etaneno, show an increase in K/Rb with differentiation. Shaw (1968) demonstrated that in ordinary igneous rocks the modal proportions of biotite and hornblende exert the most obvious control over the K/Rb ratio. From the following average K/Rb values, according to Shaw (1968): biotite (80), K-feldspar (200-300), plagioclase (300-?), hornblende (1110), it can be seen that an increase in K/Rb, i.e. a decrease in Rb relative to K, can be due to one or a combination of the following processes:

(i) crystallization and removal of biotite
(ii) accumulation of hornblende
(iii) metasomatic removal of Rb by a gas/fluid phase.

Nearly all the Okorusu alkaline rocks, in contrast with those from the other complexes under consideration, contain one or more per cent hornblende (Van Zijl, 1962). Possibility (ii) above, might thus be responsible for the increasing K/Rb ratios.

2.2.5 Zirconium

Zirconium occurs in exceptional amounts in alkaline rocks and usually increases during fractional crystallization. Various authors (MacDonald and Parker, 1969; Ferguson, 1970; Gill, 1972) reported this feature and suggested that Zr is highly soluble in peralkaline magmas. Experimental results of Dietrich (1968) and the fact that zircon and eudyalite are typically late crystallizing minerals (Marsh, 1973) support this idea. These minerals are the main carriers of Zr in igneous rocks. Zr can, however, also replace Ti in early Fe-Ti oxides and

might enter aegirine and apatite (Mineyeva, 1972). Miaskitic alkaline rocks are known to contain much higher concentrations of this element than their agpaitic counterparts.

Zircon has been identified in the white and sodalite nepheline syenites of Etaneno (Verwoerd and Retief, personal communication) in some dyke rocks at Okorusu and as a rare constituent in the nepheline syenites of Kalkfeld (Van Zijl, 1962). Zirconium does not show the expected enrichment in the more fractionated rocks of these complexes (Figs. 16, 17 and 18). Marsh (op.cit.) reported a similar decrease in Zr in the more fractionated rocks from the Lüderitz alkaline province. He suggested fractionation of zircon to account for such behaviour. The scarcity of this mineral in the Damaraland alkaline rocks renders this mechanism improbable. A more detailed look at the geo= chemical behaviour of this element is thus warranted.

The distribution of Zr (as well as other high valence elements) in alkaline complexes depends on whether the rocks are miaskitic or agpaitic (Mineyeva, 1972). The alkaline complexes of Damaraland show mixed characteristics as far as their agpaitic of miaskitic nature is concerned. They all contain rocks whose agpaitic coefficients (Na+K/Al mol.prop.) vary from less than one (miaskitic) well into the agpaitic field (up to 1,20). A plot of the Zr content versus the agpaitic coefficient of the rocks from the Etaneno, Paresis, Okorusu and Kalkfeld complexes is presented in Fig. 22. It looks as if the Zr content increases with an increase in alkalinity of these rocks (up to an agpaitic value of about 0,9) whereafter it decreases again. Mineyeva (op.cit.) showed that in the agpaitic potassic rocks of the Russian alkaline provinces zircon occurs in very limited amounts (a similar situation exists for the Damaraland rocks) and that fractionation of this mineral can not explain the decrease in Zr dis= played by the highly alkaline rocks. This author also showed that the agpaitic coefficient of sodium or potassium-rich alkaline rocks depends largely on the presence and amount of sodic pyroxene whose contribution to this coefficient is much higher than that of any other mineral. It is therefore suggested that the decrease in Zr, as displayed by the Damaraland rocks, is probably due to an easier entry of Zr into the aegirine structure under highly alkaline condi= tions. In fact, Kogarko (1970) showed that the high alkali activity of agpaitic nepheline syenitic melts causes a change in the structure of these melts and in the ionized state of the amphoteric oxides, TiO_2, Nb_2O_5 and ZrO_2. Accordingly, agpaitic rocks contain zirconosilicates, titanosilicates, titanites and niobates

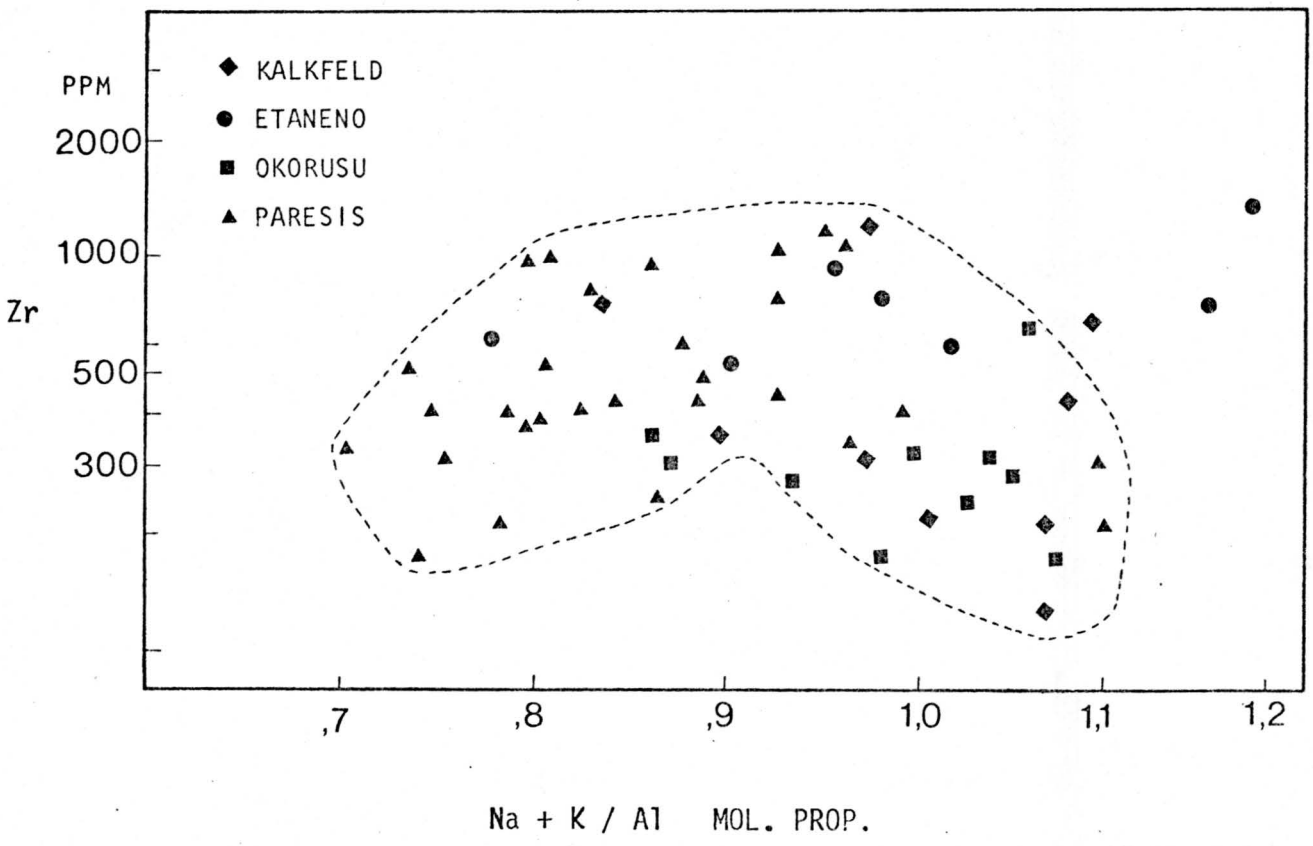


Fig. 22: Plot of Zr(ppm) versus agpaitic coefficient of alkaline rocks from Etaneno, Okorusu, Kalkfeld and Paresis.

in which these oxides act as anions. Under highly alkaline conditions the anionic role of Zr and that of Fe^{3+} and Ti^{4+} increases, and it replaces Fe^{3+} and Ti^{4+} more readily. In melts of low alkalinity the amphoteric oxides be= have as cations and are concentrated only in minerals such as zircon, sphene and titanomagnetite so that the increase in Zr in rocks of miaskitic nature is to be expected if fractionation of these phases did not occur.

2.2.6 Rare-earth elements (Ce, Y, La, Nd)

These trace elements will be described as a group because of their similarity in geochemical behaviour during magmatic processes.

The distribution of the rare-earth elements (REE) in alkaline complexes has been studied by various authors of which Vlasov (1966), Balashov (1972), Borodin, et al. (1972), Aleksiev (1973), Popolitov and Kovalenko (1973) and Mitchell and Brunfelt (1975) provide the most useful information. Although the total content of REE

generally increases with magmatic differentiation the variation in the composition within the group is very complex and remains somewhat obscure (Gerasimovsky, 1975). Examples of enrichment in Ce or Y earths as well as one kind of enrichment followed by another have all been reported (Balashov, op. cit.) Information on the behaviour of REE have so far been obtained mainly from studies of their concentration in accessory minerals (information on the REE minerals proper or the major mineral phases are very scanty) or from analyses of rocks without considering the distribution of REE among the minerals.

Aleksiev (op.cit.) studied the Rose and Vitosha complexes and showed that the total REE and Ce/Y ratios increase in rocks belonging to the middle stages of differentiation (agpaitic coef. = 0,83), whereas further differentiation caused a decrease in both these values. It has also been shown that the REE, as a group, undergo some degree of separation during differentiation and that the agpaitic coefficient of the magma control the extent to which the light REE will be concentrated in the more fractionated rocks. These studies dealt with alkaline rocks whose agpaitic coefficients vary from below 0,5 te well over 1,0. Such a spread in alkalinity values make a correlation between rare-earth contents and agpaitic coefficients unavoidable as the latter might reflect stages in differentiation and not necessarily a control over the behaviour of these elements.

The alkaline rocks of the Etaneno, Okorusu and Kalkfeld complexes show little variation in agpaitic coefficients (0,8 - 1,1) and are relatively enriched in REE. They provide an opportunity to study the REE behaviour in highly alkaline rocks which are associated with carbonatites carrying economic concentrations of these elements. An explanation for the occurence of such deposits at the southern group of carbonatites (Kalkfeld, Ondurakorume) but not at Okorusu, which is associated with similar alkaline rocks and fenitization phenomena, is needed.

2.2.6.1 Factors controlling the distribution of rare earth elements

A correspondence exists between the increase in total REE content and certain alkali indices (alk, agpaitic coefficient) for the transition from ultrabasic-alkaline to alkaline rocks (Vlasov, op.cit.). However, when dealing with alkaline rocks only, the variation in total REE and Ce/Y does not correspond to

any single petrochemical characteristic of these rocks (Aleksiev, op.cit). A nearly similar situation exists for the Damaraland alkaline rocks. Plots of total REE content, as well as concentrations of individual elements against the above coefficients, fail to indicate clear relationships. There exists, however, some sympathetic variation of the Ce/Y ratio with the agpaitic index of these rocks. Fig. 23 shows that an enrichment in the Ce earths is coupled with high alkalinity and that a degree of separation of the REE did occur during the crystallization of these magmas. The more alkaline nepheline syenites are relatively enriched in the lighter lanthanide elements. No relationship, however, exists between the Ce/Y ratios and the Thornton-Tuttle D.I. indices of the rocks.

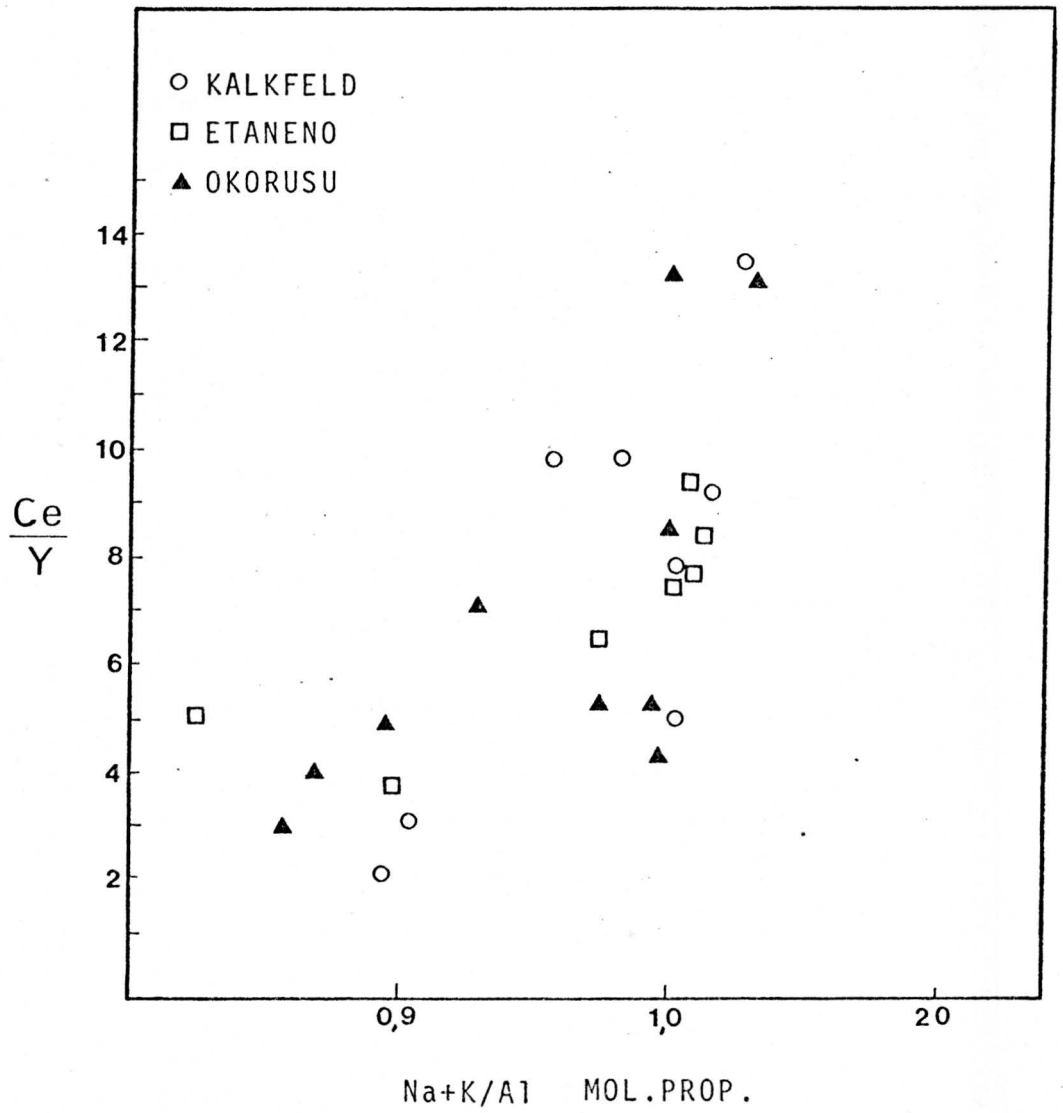


Fig. 23: Variation of the Ce/Y ratio with agpaitic coefficient of the alkaline rocks from Kalkfeld, Etaneno and Okorusu.

The increase in the light REE in the more alkaline rocks of all these complexes is probably due to the early, deep-seated crystallization of olivine and clinopyroxene. Both these minerals have D(light REE)/D(heavy REE) values less than unity (Balashov, 1970) and their fractionation would result in a relative enrichment of the melt in the lighter REE and possibly the appearance of accessory Ce-minerals.

The only chemical parameters which show a definite correlation with the REE content of these alkaline rocks are their CO_2 and F contents. Rocks with high CO_2 and F contents are relatively enriched in most of the REE (Figs. 24/25) This feature might be a clue towards an understanding of the seemingly uncontrolled distribution of these elements in most alkaline rocks. Kogarko (1974) also suggested that volatiles play an important role in the transport of ore components in hydrothermal and metasomatic processes related to alkaline rocks. She showed (1966) that the alumino-fluoride complex AlF_6^{3-} decomposes in oversaturated alkali silicate melts and argued that analogous REE complexes would do the same. If this is correct the distribution of REE in an alkaline melt would thus be related not to its halogen content but rather to oxygen with which REE supposedly form strong bonds. The lack of experimental data limits such speculation. However, the fact that the F and CO_2 contents of the alkaline rocks from Damaraland do show a correlation with their REE contents suggests that the formation of fluoride and carbonate REE complexes did play a significant role in the distribution of these elements.

It is thus suggested that the REE occur as stable fluoro-carbonate complexes in an alkaline melt and that with differentiation an increase in CO_2 and F will be accompanied by an increase in total REE. This is illustrated at Etaneno where the younger dyke rocks (Sample ET 13, Et 1 and Et 5) have some of the highest CO_2 and REE contents amongst the rocks in question. At Okorusu the dark fine-grained nepheline syenites and ijolites contain the highest CO_2 and REE contents. These magmas probably separated into immiscible carbonate (REE-rich) and siliceous (REE-poor) fractions as suggested in Chapter 7. This would account for the relatively low CO_2 and REE contents of the younger syenitic intrusions of this complex. These CO_2 and REE values are, however, still much higher than those displayed by the nepheline syenites of the Kalkfeld and Ondurakorume complexes. It thus appears that the Okorusu silicate magmas retained large quantities of REE due to their relatively high F and CO_2 contents. The immiscible

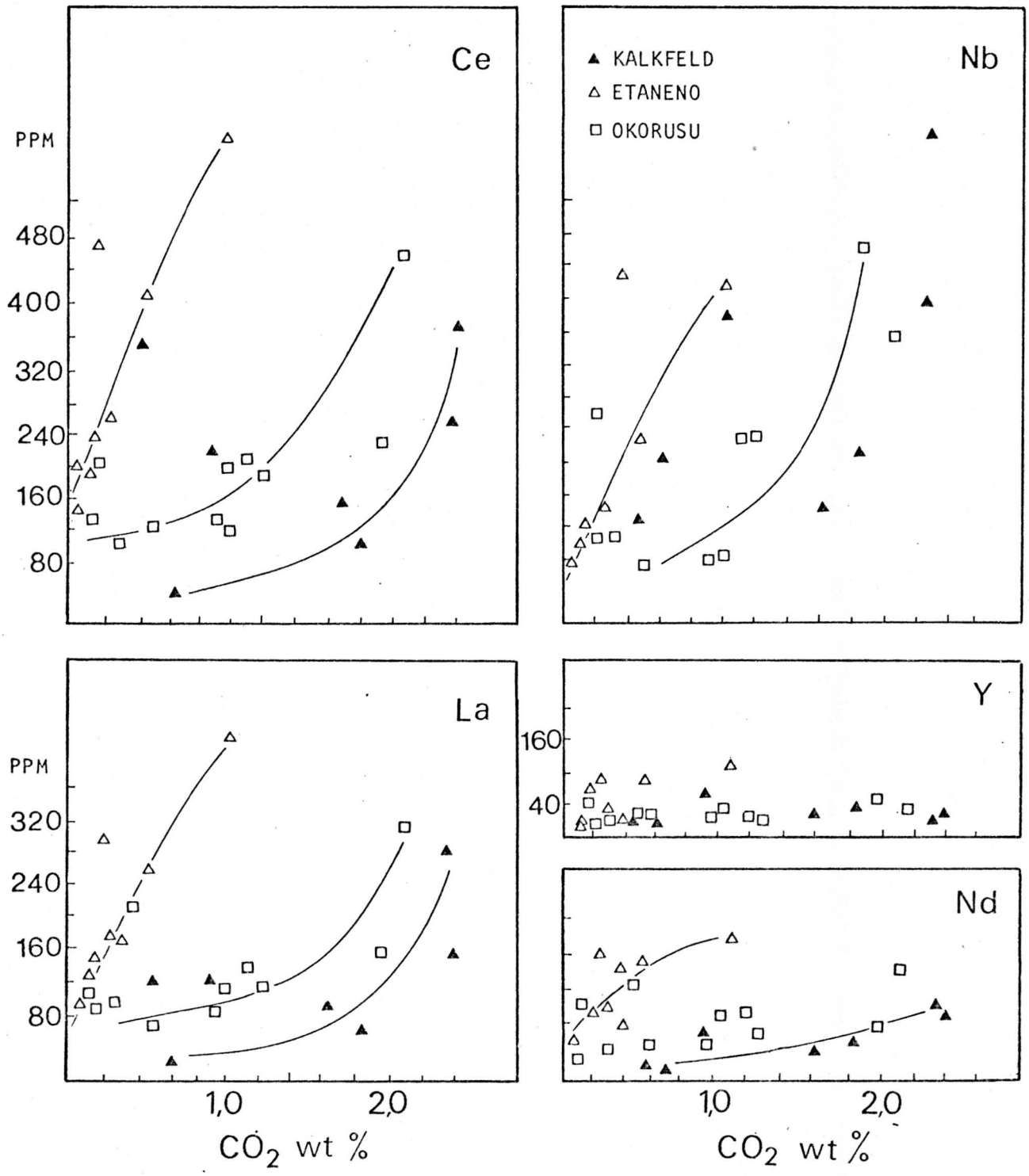


Fig. 24: Showing the variation of rare earth elements with CO_2 content of the alkaline rocks from Kalkfeld, Etaneno and Okorusu.

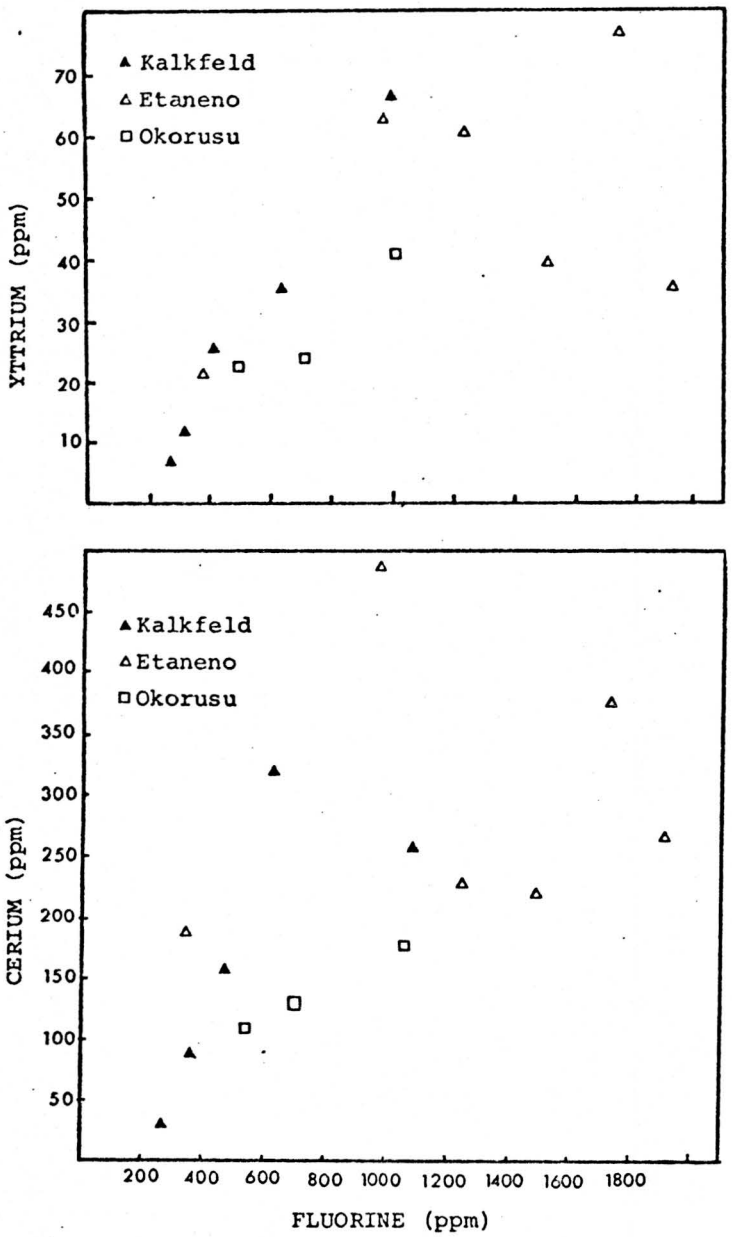


Fig. 25: Showing the variation of yttrium and cerium with fluorine content of the alkaline rocks from Kalkfeld, Etaneno and Okorusu.

carbonate fraction was therefore not as much enriched in these elements as those which developed at Kalkfeld and Ondurakorume where the alkaline rocks are much poorer in CO_2 and F. At these latter complexes a more complete extraction of the REE into the carbonate liquid probably took place.

The presence of REE fluoro-carbonate complexes in alkaline magmas is supported by the findings of Aleksandrov (1967) whose experimental work verified the existence of Nb, Nd and Y polynuclear complexes at elevated pressures and temperatures.

2.2.7 Niobium

The geochemical behaviour of Nb during magmatic processes is controlled by its substitution for Ti and Zr in igneous minerals and the formation of large complexes with oxygen in the liquid (Taylor, 1965). It thus tends to concentrate in residual liquids during fractionation and is to be found in Fe-Ti oxides, sphene and perovskite as well as in zirconium minerals. This generally accepted idea is challenged by the distribution of this element in the rocks from the Damaraland alkaline complexes. The Nb content of these rocks invariably show a decrease as the differentiation index increases (Figs. 16, 17 and 18). Theory also predicts that the Zr/Nb ratio should decrease with increasing fractionation. This is well illustrated by the alkaline rocks from the Etaneno complex (Fig. 26), where fractionation processes played a dominant role. However, the rocks from those complexes associated with carbonatite and fenite display Zr/Nb ratios which differ significantly. The syenitic dykes at Kalkfeld have ratios analogous to those of the fenitized granitic rocks of this complex. The ratios are nearly three times as high as the ratios displayed by the associated nepheline syenites - thus supporting the idea that these dykes represent mobilized metasomatic rocks. The carbonatites and some of the feldspathized syenites have Zr/Nb ratios approaching zero due to the extensive enrichment of Nb in these rocks. The same feature is displayed by the Okorusu carbonatites. The syenites and nepheline syenites of these complexes have similar Zr/Nb ratios. However, the fine-grained nepheline syenites and ijolitic bodies as well as some tinguaite dykes at Okorusu display ratios which occupy a position intermediate between that of the nepheline syenites and that of the carbonatites (Fig. 26). This can be interpreted as evidence in favour of immiscibility between a Nb-enriched carbonate and a Nb-depleted silicate liquid (see Chapter 7).

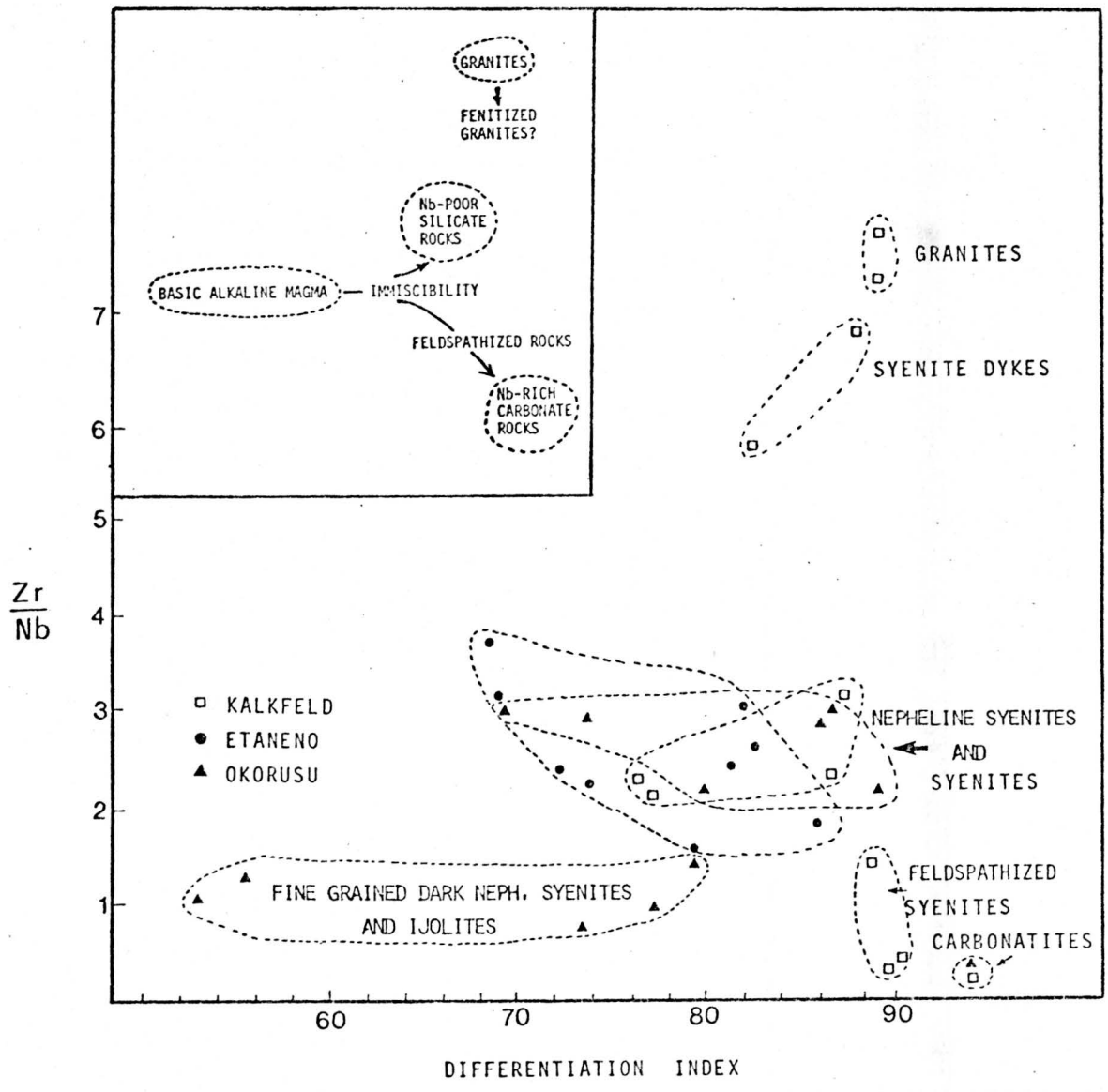


Fig. 26: Zr/Nb ratio versus differentiation index of alkaline rocks from Kalkfeld, Etaneno and Okorusu.

Borodin et al. (1972) made a survey of the Nb content of all the major alkaline provinces in the USSR and came to the conclusion that the Nb content of nepheline syenites which are unrelated to gabbroic or granitic rocks, reflects their mode of origin. He distinguished one type which has relatively low Nb contents and develops through deep crustal palingenesis whereas another, which contains eight times more Nb (average 219ppm), is considered to be of deep mantle origin. The Damaraland nepheline syenites have Nb contents comparable to the latter type.

2.3 SUMMARY

Major as well as trace element contents indicate that the partly fenitized granite ring at Kalkfeld does not belong to the alkaline suite but that it represents wallrocks of Salem granite. The syenitic rocks of this complex were to various extents affected by fenitizing fluids so that an interpretation of their chemistry in terms of magmatic processes is unjustified. K/Rb ratios indicate that alkali feldspar fractionation probably played an important role in the formation of the alkaline rocks from this complex.

The Okorusu magmas were more Na-rich than those of the other complexes. The occurrence of extensive Na-fenitization at this complex could be related to this feature. The high Na, F and CO_2 content of the Okorusu alkaline magma was responsible for relatively high concentrations of REE in this melt due to the formation of fluoro-carbonate complexes of which the Na varieties are more stable than the K varieties. The associated carbonatitic magma was thus relatively impoverished in these elements compared to those which developed at the Kalkfeld group of complexes.

Field evidence and chemical data (Chapter 6) suggest that the fluorite mineralization at Okorusu is related to late stage fluids derived from the carbonatite magma. The presence of such extensive fluorite mineralization at this complex, while similar mineralization is absent at the Kalkfeld group of complexes, suggests that either the Okorusu carbonatite magma must originally have had a higher F content than those of Kalkfeld or that erosion removed such mineralization at Kalkfeld. The fact that the alkaline rocks of Okorusu are also more volatile-rich than similar rocks at Kalkfeld and Ondurakorume suggests that the parental

magma which developed at Okorusu, and subsequently separated into a volatile-rich siliceous and carbonate fractions, was probably more volatile-rich than that which developed in the Kalkfeld area.

CONTENTS PAGE

3 THE CARBONATITES

3.1 INTRODUCTION

Von Eckermann (1948),Ginzburg (1962), Heinrich (1966), Tuttle and Gittins (1966), Verwoerd (1967) and Le Bas (1977) have dealt extensively with questions of carbonatite genesis. Amongst others, Barber (1974) and Mitchell and Brunfelt (1975) investigated geochemical acpects of carbonatitic rocks. Although experimental investigations by workers such as Wyllie (1966), Cooper, et al. (1975) and Koster van Groos (1975a) clarified some problems it also divided opinion on the crucial issue whether carbonatic magmas are of primary or secondary origin.

The study of economic deposits typically associated with these rock e.g. Cu, Nb, Fe and F, received a fair amount of attention during the last decade. These studies concentrated mainly on the mineral and chemical composition of the ore bodies rather than the chemical variation between different phases of carbonatite activity and the processes that are held responsible for the formation of the associated ore deposits. It has often been stated that the geochemical history of the associated silicate rocks must play an important part in determining the type of deposit which might form during the last stages of carbonatite activity. To what extent this applies and for what reasons, still remain obscure. Furthermore, in spite of progress in understanding carbonatite geology a few questions concerning the behaviour of volatiles and certain trace elements, the associated deuteric and hydrothermal activity and the genetic position of the carbonatite magma in a fractionation scheme of alkaline rocks, remain to be solved.

The Damaraland carbonatites are associated with a variety of silicate rocks and consist of multiple intrusions whose relative age relationships could be deter-

mined in most cases. They are furthermore associated with potential or already worked ore deposits and thus provide an opportunity to investigate some of the above-mentioned problems.

3.2 MAJOR ELEMENTS

3.2.1 The $CaCO_3$-$MgCO_3$-$FeCO_3$ system

A number of workers, such as Garson and Smith (1958), Verwoerd (1967) and Nash (1972) found that calcite is usually the first carbonate mineral to crystallize from carbonatitic melts followed first by dolomite and then by the iron carbonates ankerite and siderite. Experimental evidence (Wyllie, 1965) support this observation. The composition of the Damaraland carbonatites are plotted in terms of their $CaCO_3$-$MgCO_3$-$FeCO_3$ molecular percentages in Fig. 27.

The carbonatites of Onkurakorume can be grouped according to their field relationships into four major intrusive types, viz. the micaceous sövite, the white sövite, the apatite-rich beforsite and the amphibole or rare earth beforsite. Minor beforsitic veins probably represent the culminating phase of carbonatite activity. Analyses of these rocks plot along a definite trend, in order of relative age, towards moderate Fe and strong Mg enrichment. The increase in Mg is obviously a reflection of the increase in dolomite which becomes one of the major phases in the later (lower temperature?) intrusions. The extensive enrichment in Mg shown by the beforsite vein and the rare earth beforsite, compared with the carbonatites from the other complexes, is however, partly due to the presence of amphibole and other silicates and is not just a reflection of the increased dolomite content of these samples.

The Okorusu carbonatites are nearly pure sövites and plot near the $CaCO_3$ corner. These carbonatites are fairly homogeneous, the only significant difference between the two occurrences being the higher Fe^{3+} content of the main intrusive mass.

The different varieties of the Kalkfeld carbonatites i.e. the grey sövite, the apatite-rich sövite, the micaceous sövite and the ankeritic veins lie on a trend away from the $CaCO_3$ corner towards Fe and moderate Mg enrichment. Although no definite age relationships are known for the first three types, their areal distribution seems to indicate that the micaceous sövite might be intrusive into

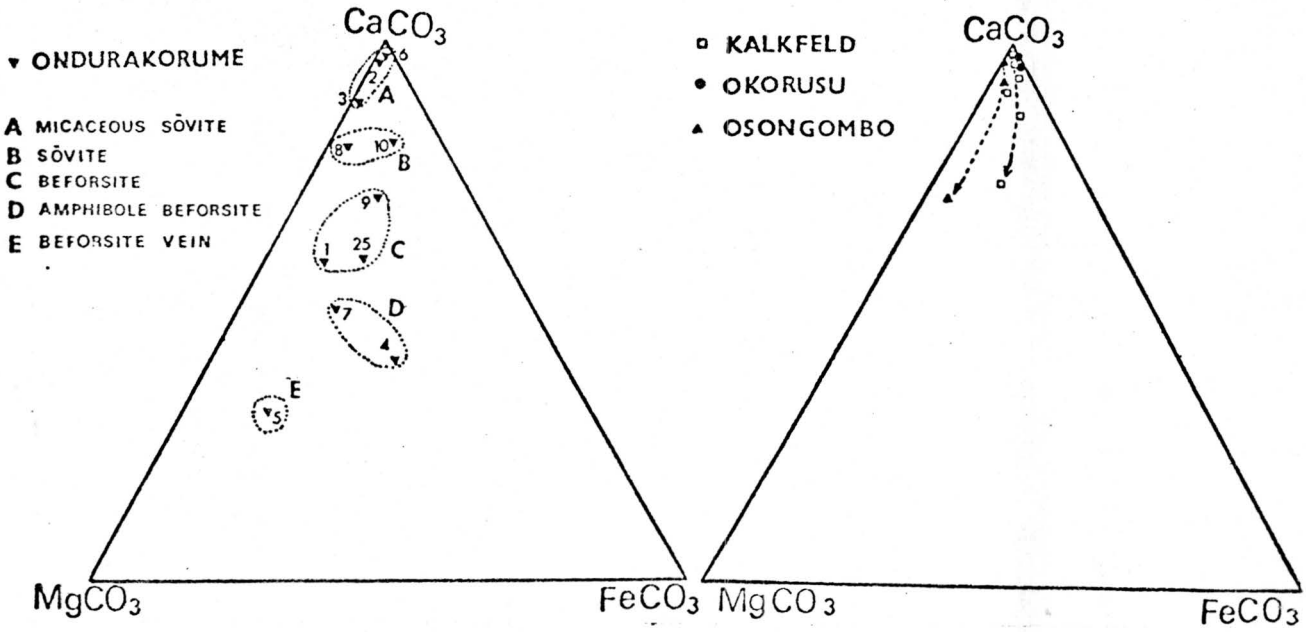


Fig. 27: Variation in the composition of carbonatites from Ondurakorume, Kalkfeld and Okorusu. Rocks plot in order of decreasing age towards the $MgCO_3$ corner.

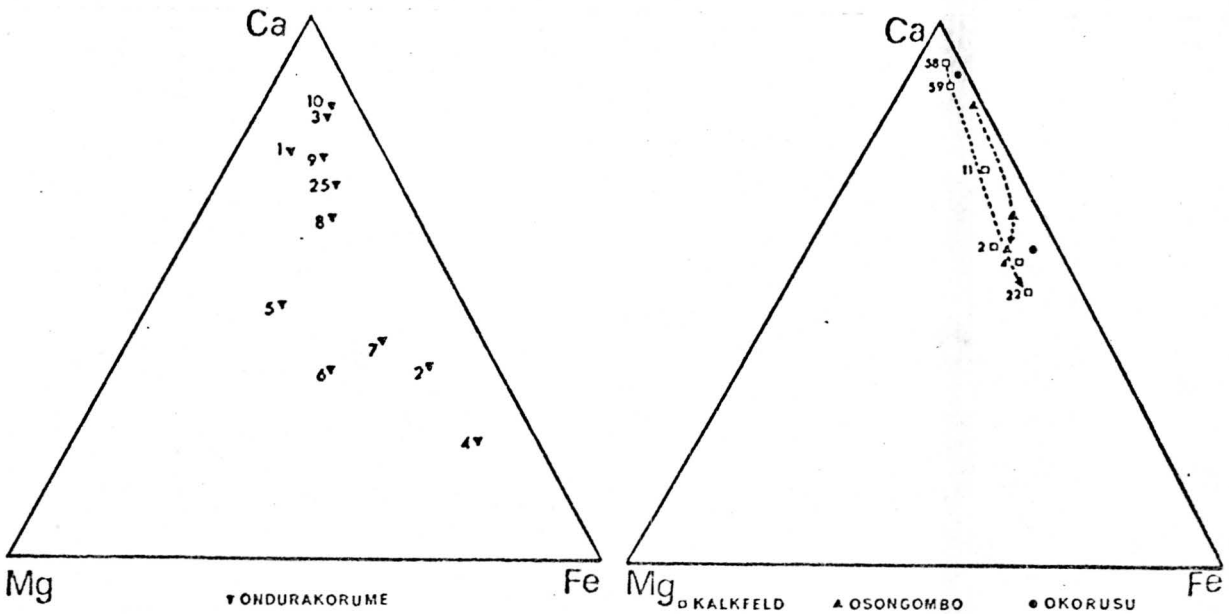


Fig. 28: Variation in the composition of carbonatites from Ondurakorume, Kalkfeld and Okorusu. The trend towards the Fe corner is irrespective of the age of the rocks.

the grey sövite whilst the apatite-rich sövite probably occurs as enrichment or segregation pods in the grey sövite. The positions of a later stage carbonatite dyke and a sample of the grey sövite extend this trend towards magnesium enrichment.

The Osongombo carbonatites, of which only three analyses are available, plot near the $CaCO_3$ corner. A late stage beforsitic dyke shows a relative increase in magnesium.

The fact that the composition of the carbonatitic rocks of the Damaraland complexes seems to vary in order of their intrusive age along a trend towards Mg enrichment supports the idea that they represent a liquid line of descent for the carbonatitic magmas which developed in this province.

3.2.2 Other major elements

3.2.2.1 Ondurakorume

The early micaceous sövites are enriched in SiO_2, Al_2O_3, K_2O, Na_2O and TiO_2 relative to the rest of the carbonatite types (Fig. 29(a)). This is obviously due to the early precipitation of silicate minerals (mainly phlogopite and feldspar). The initial Si content must have been relatively high as some of it remained in solution while the magma continued to precipitate carbonate and phosphate minerals which form the major constituents of the intrusions which followed. As already shown (Fig. 28(a)) the Ca content of the rest liquids decreased due to the early precipitation of calcite. This decrease was further enhanced when apatite appeared as a major fractionating phase. The crystallization of apatite reached a maximum during the development of the apatite-beforsite; a rock type which sometimes shows clear intrusive relationships and at others appear to have formed as segregational areas in the white sövite. Apatite becomes scares or totally absent in the later intrusive rocks, a fact which indicates that the liquid became undersaturated with respect to phosphorus. With the magma now relatively depleted in Ca, Mg, P and CO_3^{2-} the remaining Si, Na, Fe, Mg and CO_3^{2-} combined in the formation of alkali amphibole, quartz and ankerite which constitute the last intrusives.

It is apparent that the chemical variation between the various carbonatitic rocks is a reflection of their mineralogy. Incorporation of certain trace elements in

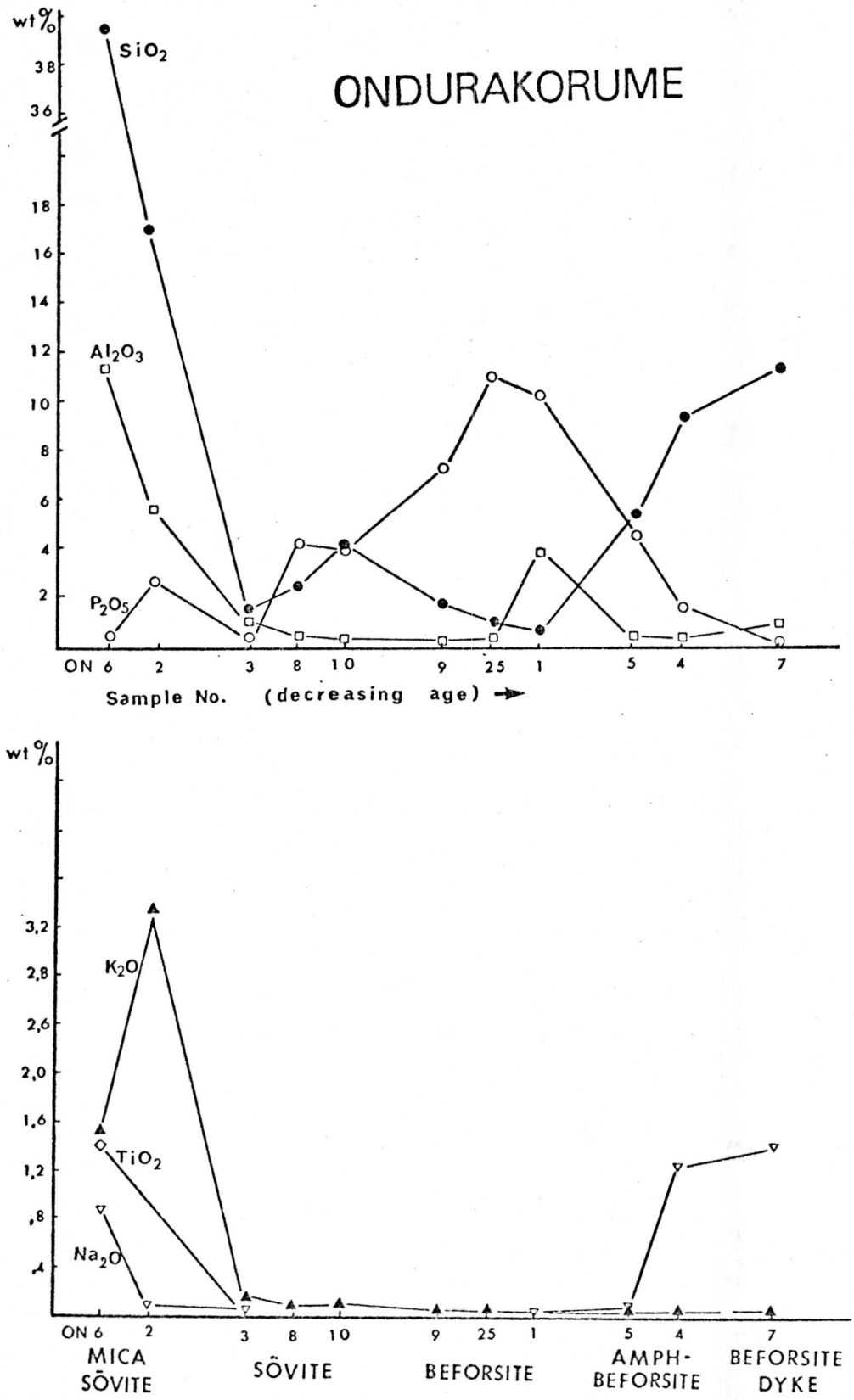


Fig. 29(a): Major element variation in the carbonatites of Ondurakorume. Abundances plotted against inferred age of the rocks as defined by field relations and the trend away from the Ca corner in the $CaCO_3$-$MgCO_3$-$FeCO_3$ triangle.

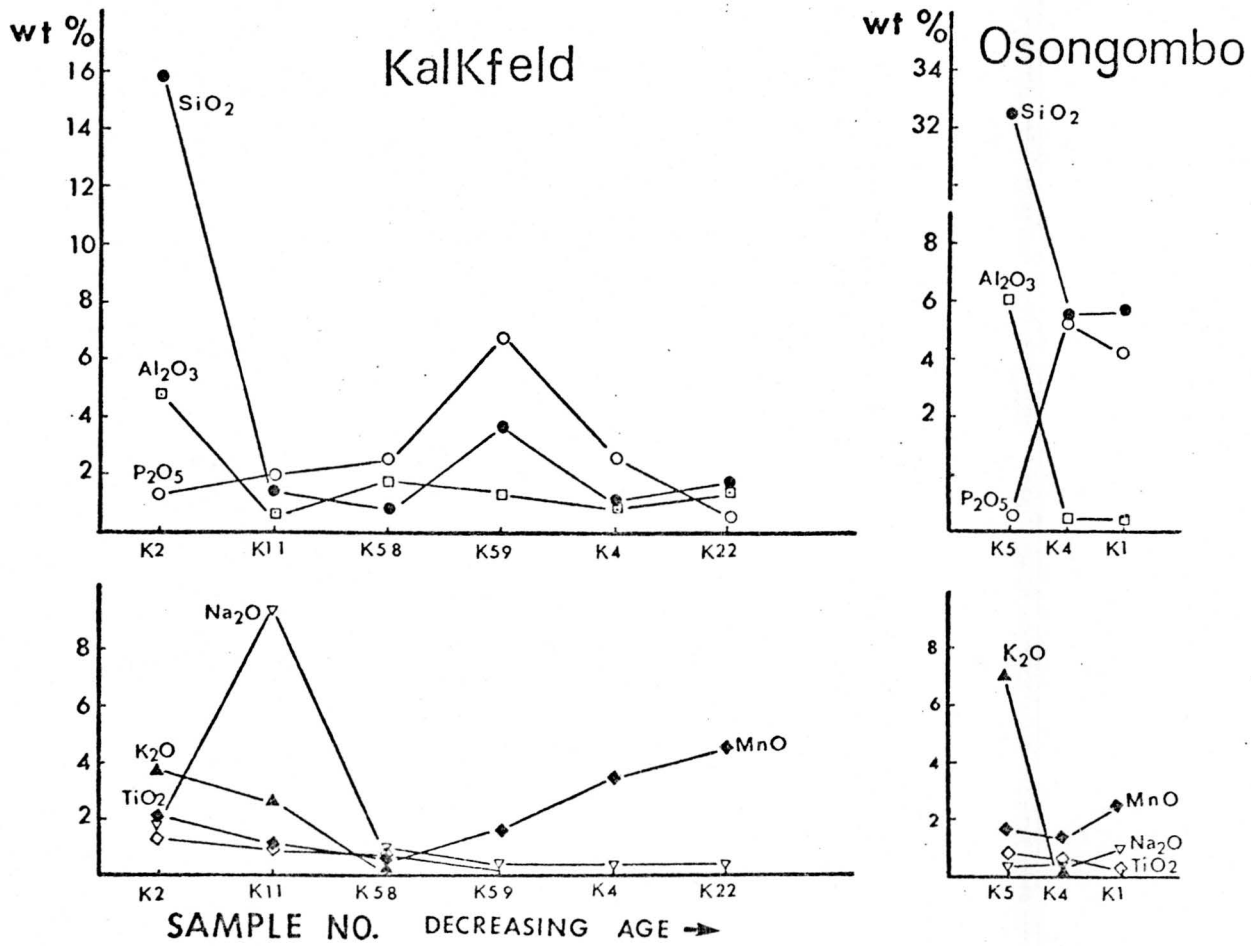


Fig. 29(b): Major element variation in the carbonatites of Kalkfeld and Osongombo. Abundances plotted against inferred age of the rocks as defined by field relations and the trend away from the Ca corner in the $CaCO_3$-$MgCO_3$-$FeCO_3$ triangle.

the crystal structures of the early precipitating carbonate and phosphate minerals and even the primary crystallization of strontianite and pyrochlore certainly occurred (de Waal and Hiemstra, 1967) but were not sufficient to deplete the hydrous rest fluids in elements such as Ba, Sr, Fe and Mn (see section 3.4.2).

3.2.2.2 Kalkfeld, Okorusu and Osongombo

The major element content of the different carbonatitic rock types from these complexes are plotted in Fig. 29(b) against their relative ages, as deduced from field evidence (Verwoerd, 1967; Van Zijl, 1962). Where these relationships are doubtful it is assumed that the age of the rocks decreased with their position away from the $CaCO_3$ corner in Fig. 27.

Trends similar to those shown by the Ondurakorume rocks seem to exist for these complexes. Sample K22 is a limonite-ankerite beforsite and represents a hydrothermally altered, Fe-enriched portion of the grey sövite and is thus not representative of the later carbonatitic liquids. Its position away from the $CaCO_3$ corner is a reflection of the extensive hydrothermal alteration it underwent.

3.3 TRACE ELEMENTS

Carbonatites and their associated alkaline rocks are characterized by a specific set of minor and trace elements which are sometimes present in concentrations high enough to render such rocks potential ore bearers. These elements include Ti, Nb, Zr, RE of the Ce group, P, F, Ba, Sr and Th. Certain ratios such as Nb/Ta, Zr/Hf, Th/U and Ce RE/ Y RE are considered diagnostic for rocks of carbonatitic affiliation. The mode of occurrence of these elements has been described (Heinrich, 1966) as:

(i) camouflaged elements in ordinary rock forming minerals, e.g. Nb in sphene;

(ii) essential components in disseminated accessory minerals, e.g. niobian-perovskite, and

(iii) essential components in minerals concentrated as major ore bodies, e.g. F in fluorite.

Earlier workers, e.g. Pecora (1956) believed that carbonatites belong to two major chemical groups, a magnetite-apatite type (with Nb minerals) and a REE type. Today it appears that the "REE type" represents the last in a series of carbonatite differentiates - a feature clearly illustrated by the Damaraland carbonatites (section 3.2.2.1). Recent studies on the trace element content of carbonatites (Kasputin, 1966; Barber, 1974) showed that the variation in most of the minor elements is a function of rock mineralogy. They failed, however, to account for the anomalous behaviour of elements such as Mn, V and Nb.

3.3.1 Barium and Strontium

Barium and strontium, due to their respective isomorphous relationships with K and Ca, occur in minor amounts in the majority of mineral species which form the rocks of alkaline/carbonatite complexes. (Erickson and Blade, 1963).

3.3.1.1 Ondurakorume

During this investigation it became apparent that the concentration of certain elements in the carbonatites of Ondurakorume show a regular variation when plotted against the age of the rock (Fig. 29). On the other hand, elements such as Mn, Ba and Fe^{3+} show irregular trends on a similar plot and may perhaps be ascribed to late stage processes (cf. 3.4.1).

Strontium shows a relatively smooth increase with differentiation (Fig. 30). Quon and Heinrich (1965) showed that the Ba and Sr content of carbonate minerals decrease with decreasing age of the carbonate species. This is supported by the experimental work of Froese and Winkler (1966) who showed that at constant pressure the Sr content of aragonite should decrease with a decrease in temperature. The high Sr content of the later intrusives of Ondurakorume is thus obviously due to the increased precipitation of strontianite (de Waal, 1968) and is not due to an increased Sr content of the carbonate minerals. This increase in Sr during differentiation contrasts with the studies of Barber (1974) who showed that the younger carbonatite varieties at the Homa and Wasaki carbonatites, W. Kenya, contain less Sr than the earlier intrusives. These carbonatite complexes are much poorer in Sr than the Damaraland occurrences and, apparently do not contain strontianite. The decrease in Sr in the Wasaki and Homa carbonatites could therefore be due to a poorer entry of this element in the carbonate

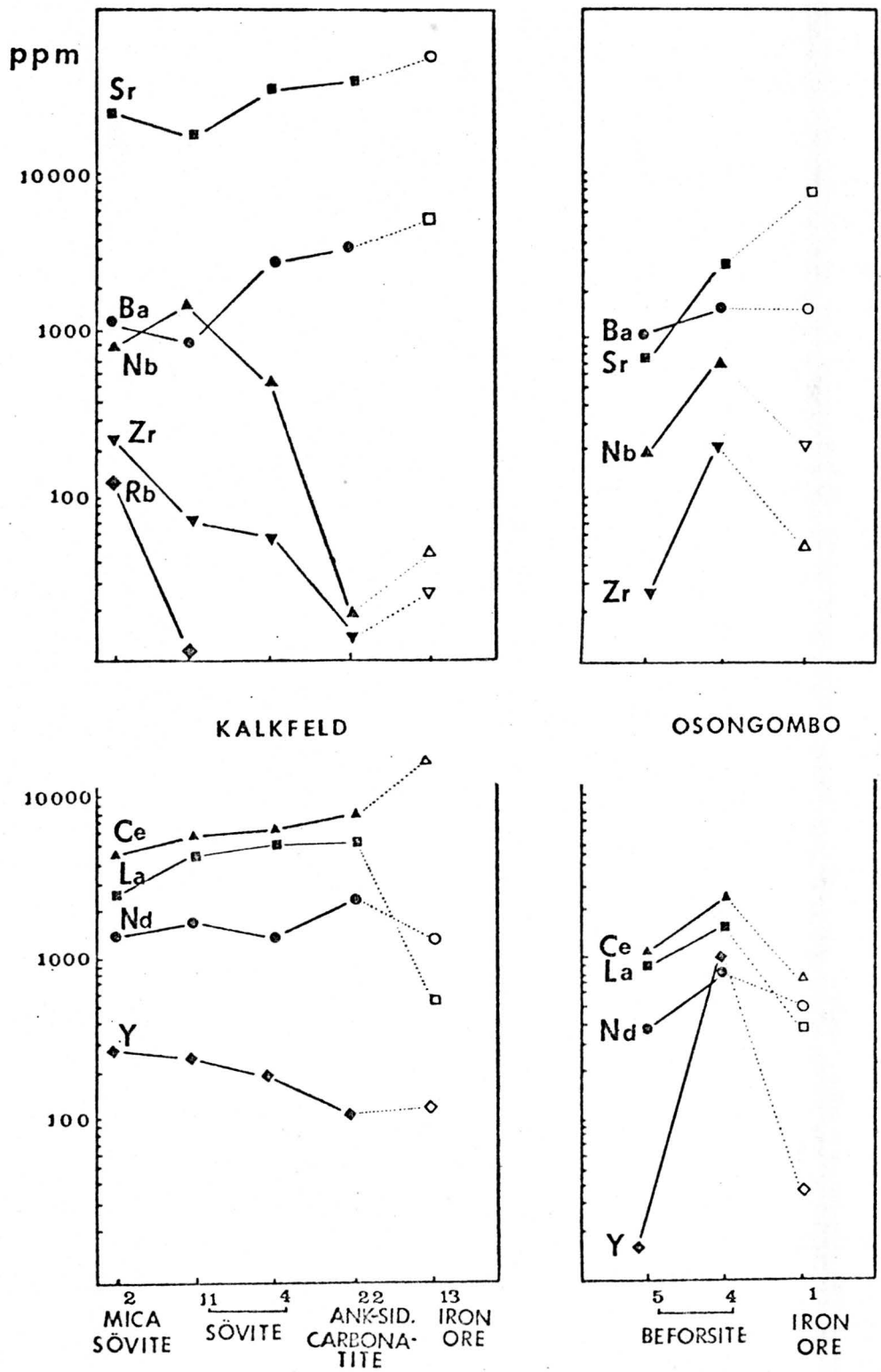


Fig. 30: Trace element content of the Ondurakorume and Okorusu carbonatites plotted against their inferred ages.

mineral structures at lower temperatures. However, Sr was apparently concen= trated in a fluid that feldspathized (fenitized) the country rocks, which, as shown by Barber (op.cit.) contain anomalous concentrations of Sr.

3.3.1.2 Kalkfeld, Okorusu and Osongombo

The behaviour of Sr and Ba in the carbonatitic rocks from these complexes is similar to that shown by the Ondurakorume rocks (Fig. 31). As at Ondurakorume Sr is depleted in the associated iron-ore veins whereas Ba shows and increase. The low Sr content of the hematitic iron-ore lenses of Kalkfeld and Okorusu suggests that the hydrothermal fluids associated with these carbonate magmas were relatively poor in this element due to its earlier removal as strontianite. The Osongombo sövite and beforsite have the lowest Ba and Sr content of all the Damaraland carbonatites. No strontianite or any other Sr carbonate was detec= ted in these rocks, so that Sr probably entered an associated water-rich phase as in the case of the Homa and Wasaki carbonatites. The presence of a Fe-rich phase of hydrothermal alteration at Osongombo as described by Verwoerd (1967) supports this ideas. It is therefore no suprise to find the Osongombo iron-ore relatively enriched in Sr compared to its associated carbonatitic rocks as well as to the iron-ore deposits of the other complexes (Fig. 30).

3.3.2 Rare-earth elements (REE)

Various trends have been detected in the distribution of REE in the different types of carbonatitic activity (Balashov and Pozharitzkaya, 1968). Even where a magmatic origin is envisaged the composition and trends of REE do not seem to be the same for all occurrences (Barber, 1974; Van Wambeke, et al., 1964). It has been suggested that the variable REE behaviour in igneous carbonatite com= plexes is related to differences in the regional and structural setting, or differences in depth of formation or level of exposure (Balashov and Pozharitz= kaya, op.cit.).

The worlds largest concentration of RE minerals occurs in the Mountain Pass car= bonatite in San Bernadino County, California. RE mineralization is also pre= sent in the carbonatites of Damaraland of which the Ondurakorume deposit is the most important.

Various intrusive pulses of carbonatitic magma have been recognized in this complex. The youngest, viz. the amphibole beforsite, carry economically in=

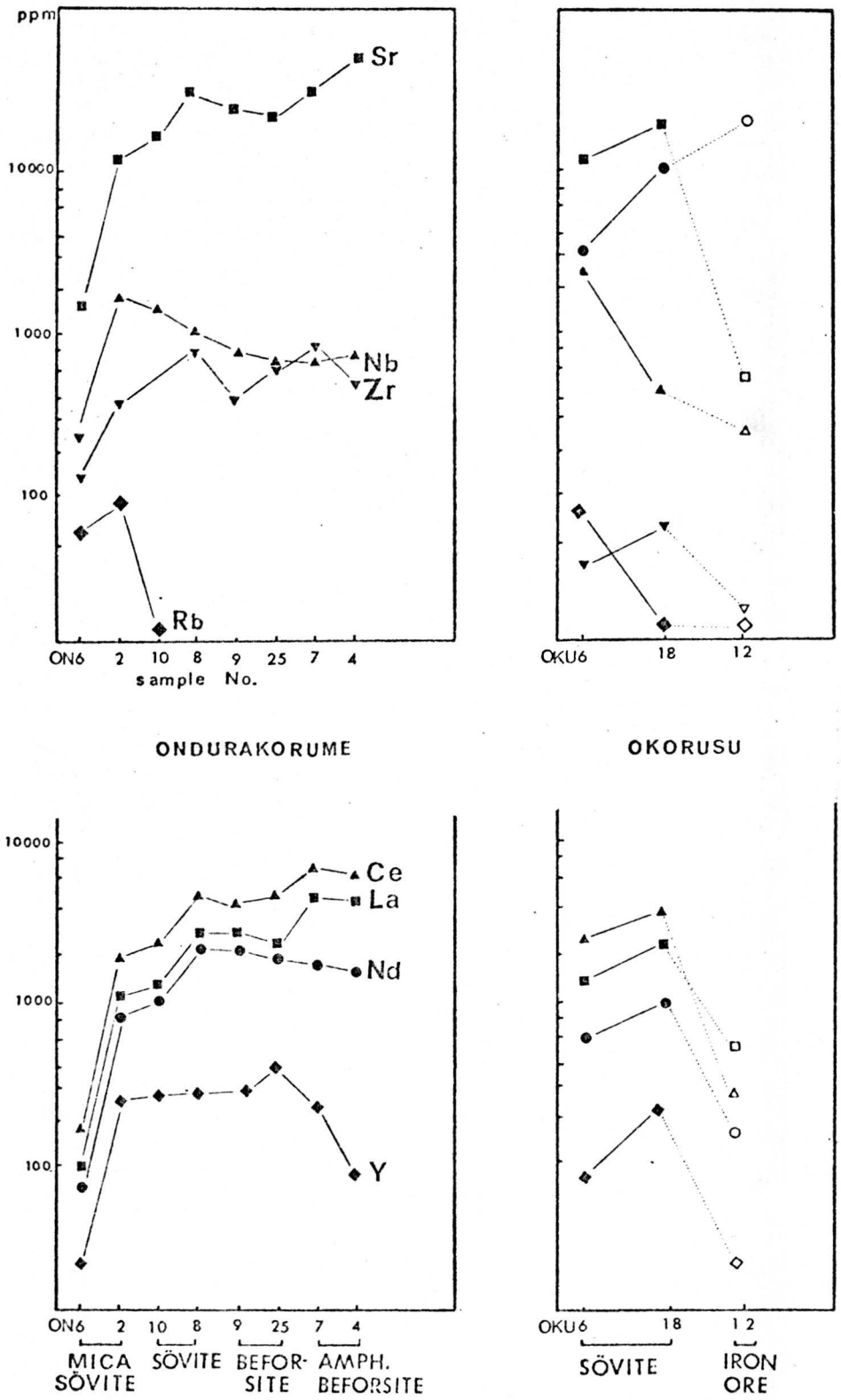


Fig. 31: Trace element variation in the Kalkfeld and Osongombo carbonatites. Abundances plotted against relative age of the rocks as inferred from the trend away from the $CaCO_3$ corner in the $CaCO_3$-$MgCO_3$-$FeCO_3$ triangle.

teresting concentrations of rare earth minerals.

The REE contents of the different carbonatitic rock types in the Damaraland complexes are plotted relative to their inferred ages in Figs. 30 and 31. It can be seen that in the case of Ondurakorume Ce, La and Nd increase regu= larly towards a maximum in the amphibole beforsite dykes. Yttrium on the other hand, shows an initial increase but decreases markedly in these dykes.

Noteworthy is the fact that the Kalkfeld carbonatites show a slight but similar variation in these elements between the early and late intrusive. It thus seems that with an increase in total REE, a pronounced separation between the light and heavy REE occured during the crystallization of these RE bearing car= bonatite magmas.

At Ondurakorume the early micaceous sövite and certain varieties of the sövites proper carry pyrochlore and subordinate amounts of rare earth minerals such as monazite and ancylite. These minerals occur in greater amounts in the beforsi= tic rock types and abundantly in the RE amphibole dykes. The REE content of some of the earlier sövites is similar to that of the later beforsitic types. These elements should thus be dispersed mainly between the major rock forming minerals of the earlier intrusives. Balashov and Pozharitzkaya (op.cit.) showed that the REE contents of dolomite and ankerite are less, by factors of 4-5, than those of calcite which crystallized at higher temperatures. With dolomite and ankerite replacing calcite as the main crystallizing phases at lower tempera= tures the degree of dispersal of REE amongst the major minerals became less with a resultant increase of REE in the rest liquids. The emplacement of the last carbonatic liquid at Ondurakorume resulted in the formation of amphibole befor= site dykes with their relatively large concentrations of RE minerals.

The increase in the total REE content of the youngest intrusives at Kalkfeld might also be due to the increased precipitation of RE minerals because ankerite and siderite, which are the main constituents of these rocks, can probably not account for the high REE content.

3.3.2.1 The separation of rare-earth elements

Experimental evidence presented by Aleksandrov et al. (1965) indicates that at low temperature (200-300^{o}C) the light lanthanide carbonate complexes are much

less soluble (stable?) in alkali carbonate solutions than those of the heavy REE. One may conclude that the RE minerals which precipitate from the final magma fractions will be relatively enriched in the light REE. The heavy REE would probably remain soluble and accumulate in the final water-rich phase which remains after the carbonate melts have solidified. Evidence in favour of such a conclusion is provided by the distribution of Ce and Y in the car= bonatites from Damaraland. Fig 32 shows that the last intrusive phases are generally quite strongly enriched in Ce. It is significant, in this respect, that the Fe-ore lenses associated with all the Damaraland carbonatites have Ce/Y ratios much lower than those of the last carbonatitic intrusions of these complexes. (Fig. 32). This indicates that the Fe-rich hydrothermal fluids were relatively enriched in the heavy lanthanides. This idea is supported by the observation of Balashov and Pozharizkaya (1968) who showed that the ankerite phase from the outer, hydrothermally altered, parts of ankeritic bodies which does not contain RE minerallization is enriched in heavy REE whereas ankerite from carbonatites enriched in REE are relatively poor in heavy REE.

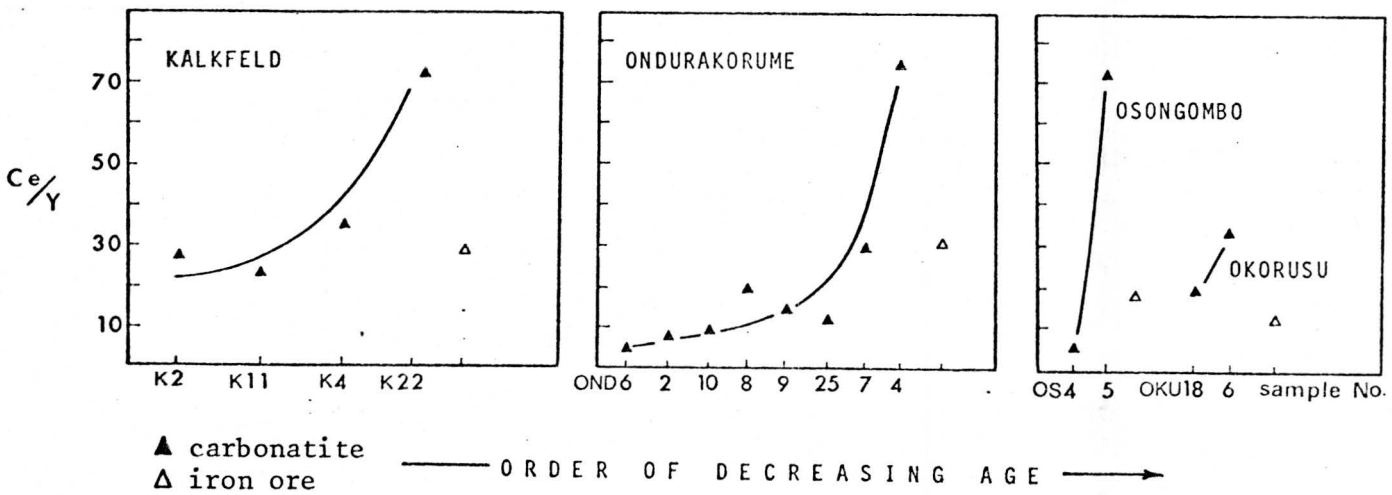


Fig. 32: Ce/Y ratios of the carbonatitic rocks from Kalkfeld, Ondurakorume, Osongombo and Okorusu plotted against their inferred ages. Open triangles indicate the ratio of the associated iron ore.

Balashov and Pozharizkaya (op.cit) consider the role of the alkali activity of the melt as an important parameter in the distribution of REE in carbona= tite intrusives. The Damaraland carbonatites do not support this view as their sodium and potassium contents are very low (≈ 1,5wt %), except for the micaceous varieties, and do not show any relationship with the gradual increase or the separation of the REE as displayed by these complexes.

3.3.3 Niobium

Niobium is one of the most characteristic elements of carbonatites and alkaline rocks. Erickson and Blade (1963) suggested that,

(i) the tendency of Nb to concentrate in residual magmas and,
(ii) the availability of favourable mineral structures to ac= commodate Nb, determine the distribution of this element in these rocks.

Barber (1974) found an increase in Nb in the younger carbonatites of the Homa and Wasaki complexes. Van Wambeke, et al. (1964) described a similar feature for the Kaiserstuhl carbonatites. A noticeable absence of data on the distri= bution of Nb is found in the descriptions of carbonatite complexes by Russian workers.

The Damaraland carbonatites provide useful information on the distribution of Nb during the evolution of a carbonatitic melt. These carbonatites have much higher Nb contents than their associated alkaline rocks. They also contain more Nb than similar rocks from the Homa, Wasaki and Kaiserstuhl complexes. The high Nb content of the Damaraland carbonatites seems to be connected with the relative= ly low concentration of this element in their associated alkaline rocks. The early alkaline silicate magmas of these complexes did not crystallize perovskite, pyrochlore or sphene in any appreciable amounts so that the carbonatite magmas which evolved from these melts were able to concentrate large amounts of Nb. However, pyrochlore precipitated from the highly Nb-rich carbonate melts simul= taneously with the early calcite and micaceous minerals causing the rest liquids to become depleted in this element. Such a depletion is displayed by the Kalk= feld, Okorusu and Ondurakorume carbonatites and is illustrated in Figs. 30 and 31.

3.3.4 Zirconium

The occurrence of this element in carbonatites is controlled mainly by the presence of zircon, zirconian garnets and baddeleyite. Zirkelite and calzirtite have been described from carbonatites in Siberia and Brazil (Van der Veen, 1965). Pyrochlore may contain large concentrations of Zr whereas minor or trace amounts have been detected in feldspar, pyroxene, amphibole, biotite and magnetite.

The distribution of Zr in the various Damaraland carbonatites are not consitent. The Kalkfeld and Okorusu carbonatites are relatively depleted in this element compared to those of Ondurakorume. They furthermore show a marked decrease in Zr with differentiation (Fig. 31). This can perhaps be accounted for by the relatively large amounts of pyrochlore (admitting Zr) which crystallized in the early micaceous sövites at Kalkfeld (Verwoerd, 1967). On the other hand, the early micaceous sövites of Ondurakorume contain among the lowest Zr and highest Nb contents of any of the carbonatitic rocks from this complex. However, the intrusions which followed the emplacement of the micaceous sövite, i.e. the sövites proper and beforsitic types, contain much larger concentrations of Zr and show a slight increase with fractionation. An explanation for the contrasting behaviour of Zr in the Ondurakorume and Kalkfeld carbonatites is thus needed.

A plot of the Zr versus Nb contents of the various carbonatitic rocks studied (Fig. 33) exemplifies this behaviour and provides possible answers. Both Ondurakorume and Kalkfeld show a marked decrease in Nb with differentiation which has been ascribed to the early precipitation of pyrochlore (Figs. 30 and 31). In the absence of Zr minerals (of which none have so far been identified in the Kalkfeld rocks) crystallization of pyrochlore would also deplete the rest liquids in Zr. This appears to have been the case for the Kalkfeld and Okorusu magmas where Zr shows a sympathetic decrease with Nb. However, the Ondurakorume rocks show that in Zr-rich carbonate melts the fractionation of pyrochlore does not affect the Zr content significantly. In fact the Zr content of these melts seems to increase with a decrease in Nb (Fig. 33). In this case zircon appeared as an accessory mineral in the last fractions as reported by de Waal and Hiemstra (1967). Comparative microprobe study of Kalkfeld and Ondurakorume pyrochlores would prove or disprove this suggestion.

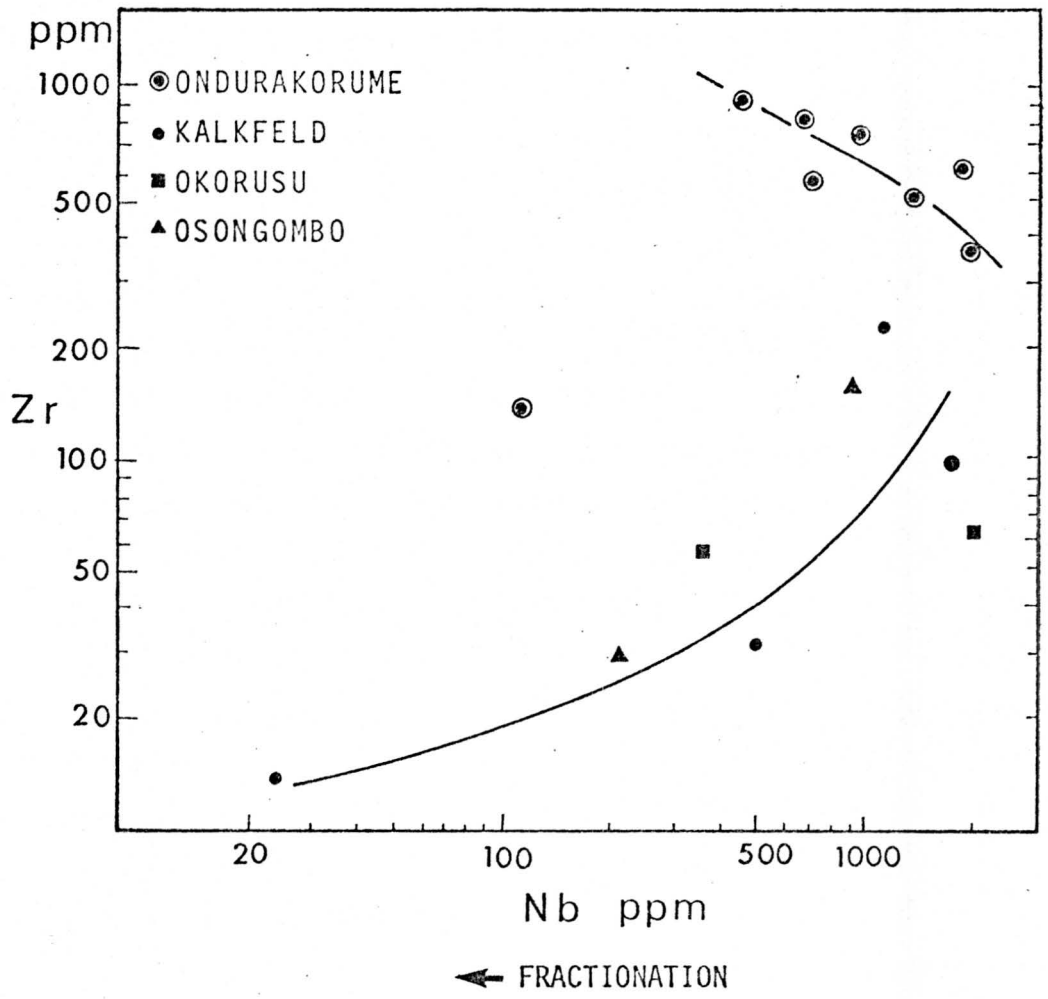


Fig. 33: Plot of the Zr versus Nb content of the carbonatitic rocks from the Damaraland carbonatite complexes.

3.4 LATE STAGE PROCESSES

The emplacement of the Damaraland carbonatites was accompanied by extensive syn- or post-intrusion hydrothermal activity (Table 2). The distinction between the last stages of carbonatite magmatism and deuteric/hydrothermal activity is usually not clearly discernible. Amphibole and rare-earth beforsite dykes, ankerite-limonite veins and beforsite veins and dyke-like bodies represent the last stages of such magmatism. Coarse-grained veins consisting of monomineralic phases such as calcite, fluorite, barite and quartz as well as the replacement hematite ore body at Kalkfeld are here considered as products of hydrothermal fluids. These fluids were markedly different from those responsible for the feldspathization at these complexes and were probably not in equilibrium with any of the carbonatitic magmas.

Table 2: Elements introduced during hydrothermal processes associated with the Damaraland carbonatites.

	Elements introduced											
	Fe	Sr	Pb	Th	Ca	Ba	P	S	Si	F	C	Mn
ONDURAKORUME												
replacement of calcite and magnesio-dolomite by par= ankerite and strontianite	x	x										x
Fe-ore lenses and Fe-staining in most rock types	x			x								
veins of barite, calcite, apatite, galena			x		x	x	x	x		x	x	
KALKFELD												
massive replacement Fe-ore body	x			x								
thin veins of calcite, barite and apatite					x	x	x	x		x	x	
veins of Mn-ore (ground water?)												x
clay minerals on joints (ground water)												
OSONGOMBO												
oxidation and Fe-enrichment of beforsite	x											
quartz and barite as in= terstitial patches						x		x	x			
OKORUSU												
Fe-ore lenses	x											
fluorite-quartz veins and replacement bodies				x	x				x	x		
Mn-ore on joints (ground water?)												x

3.4.1 Major elements involved

Most of the Ondurakorume rocks studied show some or other form of replacement. The nepheline syenite is traversed by numerous cracks and joints filled by analcite, calcite, chlorite and limonite. Calcite and quartz occur in the apatite beforsite as thin veins and as a replacement product of some carbonate minerals. The calcite of the white sövite shows incipient replacement by par= ankerite and strontianite. The post-carbonatite dolerite dykes are highly al= tered and contain amygdales filled with calcite, chlorite, zeolite and analcite with its feldspar being extensively saussuritized. The existence of a gaseous-fluid phase which changed the original chemistry of the rocks of this complex thus seems undeniable. A distinct trend towards Fe enrichment has already been demonstrated for the Ondurakorume carbonatites (Fig. 28) but this trend is not related to the order of crystallization. This means that the Fe^{3+} en= richment which occurred to a variable extent in most of the intrusive phases is not the result of a particular fractionation scheme but is probably due to late stage deuteric/hydrothermal processes. The variation in certain minor element contents could also be a result of these processes as described in the following section.

The carbonatites of Kalkfeld and Osongombo show a similar enrichment in Fe^{3+} (Fig. 28) as can be expected considering the development of extensive hematite replacement bodies in these complexes.

3.4.2 Minor elements involved

It has been shown previously that at Ondurakorume, elements such as Sr, Zr and the rare earths were removed from the carbonatitic magma by the precipitation of strontianite, monazite, zircon, etc. It is proposed that after the crystal= lization of the major carbonate phases, Fe^{3+}, Mn^{2+} and Ba^{2+} became the dominant cation species in a rest fluid which had at this stage acquired a hydrothermal nature. This fluid, which initially occurred as an interstitial medium moved upwards and affected, to various degrees, most of the carbonatite units on its way to the surface. In this way secondary enrichment during the deuteric/hydro= thermal stage could be held responsible for the variation in the Fe, Mn and Ba content of these rocks. This statement is to some extent verified by Fig. 34(b) in which the Ba and Mn contents of the Ondurakorume rocks are plotted in order

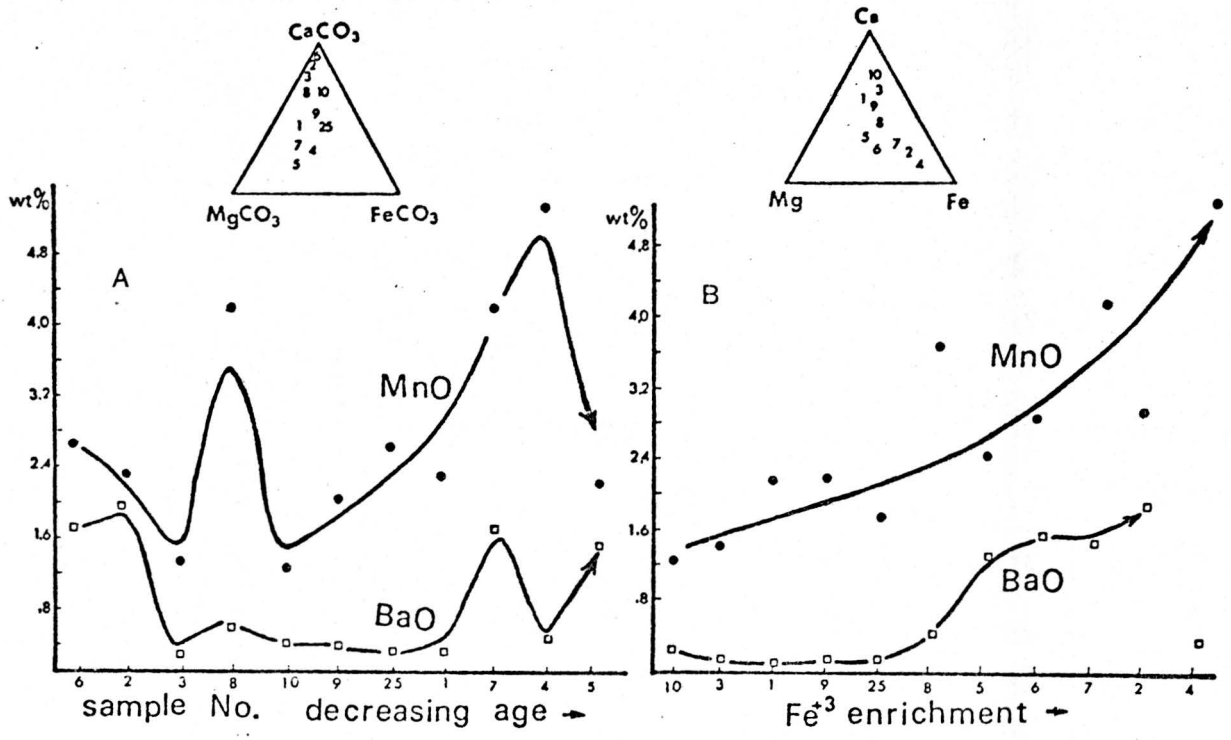


Fig. 34: BaO and MgO contents of the carbonatitic rocks of Ondurakorume plotted (A) in order of decreasing age after Fig. 27 and (B) in order of increasing Fe content after Fig. 28.

of increasing Fe content as indicated by the Fe-Ca-Mg diagram (Fig. 28). The relatively smooth increase in Mn and Ba, as plotted in this sequence, contrasts sharply with the irregular variation in the concentration of these elements when plotted relative to the intrusive age of the rock. (Fig. 34a). It is concluded that, as in the case of Fe, the Mn and Ba contents of the Ondurakorume rocks are due to the overprinting effect of a deuteric process and do not represent a trend caused by fractionation of crystallizing minerals.

Apart from the difficulty of distinguishing late-magmatic and post-magmatic stages in carbonatite genesis, a further distinction between deuteric and hydrothermal processes may be necessary. According to Heinrich (1966) this distinction is difficult and sometimes impossible to make.

It is suggested here that the processes responsible for the mineral alterations in the Damaraland carbonatites and the concommitant enrichment of the rocks in Fe, Mn and Ba be termed deuteric, whereas the formation of distinct hematite, barite

and Mn veins and Fe-ore replacement bodies are due to processes that can be described as hydrothermal. The fact that the same elements are involved in both processes clearly indicates their common origin and gradational relationship. The final water-rich rest fluid, after its deuteric effect on the crystallizing or already crystallized rock, manifested itself in the formation of monomineralic vein deposits. Which mineral(s) precipitated in these veins probably depended on the composition of the fluid at that stage and on the thermodynamic conditions which prevailed.

3.4.3 The low-temperature oxidation (martitization) of magnetite

The previous section indicates that deuteric/hydrothermal processes played an important role in the formation of the carbonatitic rocks of Damaraland. This is an aspect of carbonatite geology which received little attention in the past and of which not much information is available.

Deuteric/hydrothermal processes are generally regarded as of an oxidizing nature. Magnetite is very susceptible to oxidation and the extent of its martitization was investigated as a possible indicator of the intensity of oxidation (alteration) which a rock was subjected to. A previous investigation concerning the composition of magnetite from carbonatites (Prins, 1972) suggested such a possibility.

Drill-core samples from Ondurakorume and Okorusu were used in order to eliminate the possible superimposed oxidation effects which weathering processes could have had on these rocks. In order to evaluate the validity of the results obtained from the Damaraland carbonatites a study of the martitization of magnetite from a number of other complexes are included. The sample numbers and carbonatite complexes dealt with are as follows:

Complex	Sample number	Complex	Sample number
Ondurakorume	On-3, On-4, On-25	Chishanya	D366
Kalkfeld	K-2, K-11, K-51	Dorowa	D347
Okorusu	Oku-22, Oku-23	Galapo	D323
Osongombo	Os-4, Os-5	Oldonyo Dili	D472
Homa Mountain	D277	Twee rivier	D368
Sukulu	D94	Toror Hills	D135

Magnetite from the aforementioned samples show a definite sequence of progressive oxidation features. These features can be distinguished from those described by Wilson and Watkins (1967) which develop during cooling of a magma. The main difference between these two types of oxidation features is that magnetite which has been affected by low temperature solutions shows fine martite lamellae which invade the grain from its border inwards whereas high temperature oxidized magnetite shows broad martite lamellae which, even in the early stages of oxidation, develop across the whole grain.

Wilson and Watkins (1967) proposed a scheme by which high temperature oxidized titanomagnetite can be classified according to four distinct stages of progressive oxidation. The low temperature oxidation features of magnetite provide a similar basis for a scheme, as presented below, which can be used to classify the extent of alteration of such rock samples.

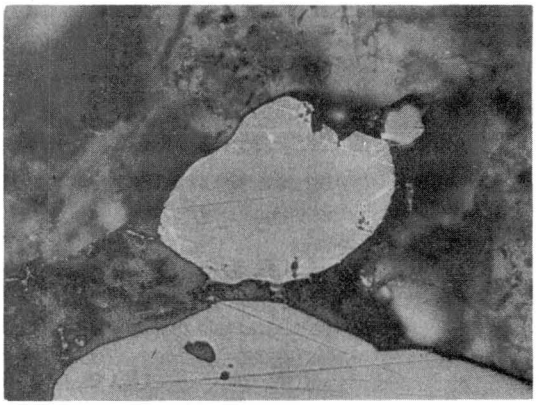
Class 1. Homogeneous magnetite grains. A few very thin hematite lamellae, scattered individually along the edges of some grains, are occasionally present. Figs. 35(a) and (b).

Class 2. Magnetite grains are rimmed by a martitized zone which invades them along (111) planes. The interior still remains homogeneous except for hematite lamellae that surround inclusions or exsolved spinel phases. A fine-grained spinel phase, which exsolves during the oxidation, appears in some lamellae. Fig. 35(c).

Class 3. Martitized 'areas' appear, which extend across the grains leaving relict patches of the isotropic magnetite host. Hydrated iron oxides, released during the martitization, occur along grain boundaries around these grains. Fig. 35(d).

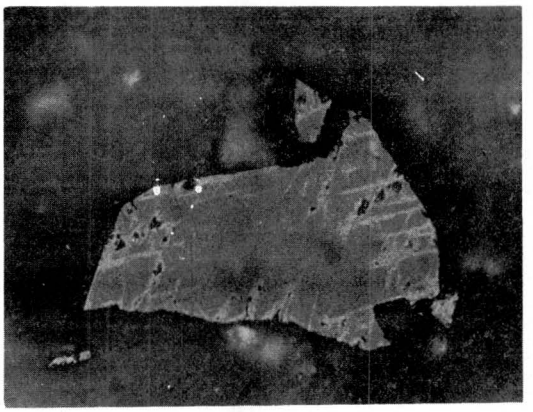
Class 4. More intense alteration results in the disappearance of the lamellar habit of the hematite. The grains are crowded with spinel inclusions and are usually surrounded by extensive iron stains. Fig. 35(e).

To minimize the subjectivity of the scheme and to make the definitions more rigid the following rules can be applied.



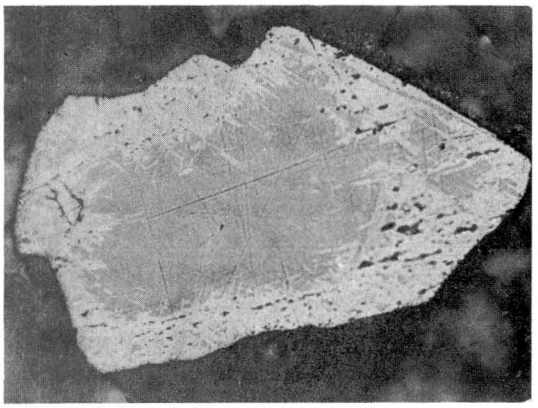
A. Class 1.

Homogeneous magnetite grains with a few scattered martite lamellae along their grain edges. Sukulu. Sample D94. (x 100, oil immersion in plane polarized light).



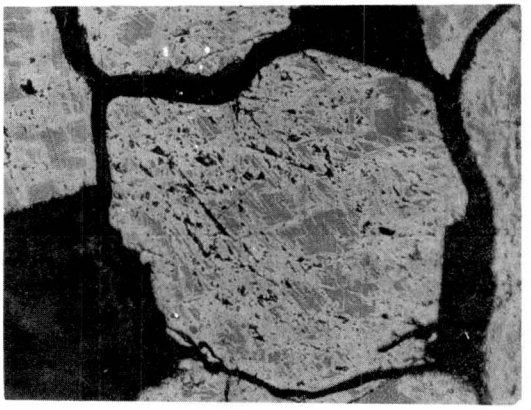
B. Class 1.

Although martite lamellae extend nearly across the grain, no continuous rim of hematite is formed so that this sample still falls in class 1. Very small grains, usually suggest a higher martitization index than the actual case. D94. (x 250, oil immersion in plane polarized light).



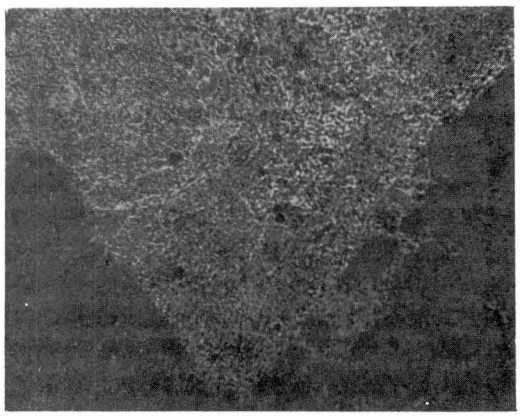
C. Class 2.

A magnetite grain rimmed by a martite zone while its interior remains homogeneous. Black spots are spinel which exsolved during martitization. Homa Mt. Sample D277. (x 100, oil immersion in plane polarized light).



D. Class 3.

Martitization extends across the grains leaving relict patches of magnetite. Chishanya. Sample D366. (x 100, oil immersion in plane polarized light).



E. Class 4.

The whole grain consists of hematite and is crowded with exsolved spinel. Diffusion of iron from the grain during oxidation resulted in secondary iron oxides surroundig it. Sample 135 (x 60, crossed nicols).

Fig. 35: Magnetite grains showing progressive martitization features

Whenever a specimen seems to fall between two classes, it is put deliberately in the lower class, except between classes 1 and 2 when it is raised into class 2 so that the extreme classes 1 and 4 are sharply defined. It is obvious that small grains of magnetite would indicate a relatively higher martitization state than larger ones. (Fig. 35b). A minimum diameter of 0.05 mm is thus proposed for the oxide grains in order to be used in this classification.

In the carbonatite specimens there was little difficulty in allocating a specific martitization state to the whole sample. Hand specimens of Kalkfeld (K2, K11, K51) and Osongombo (Os4, Os5) were highly altered and belong to Class 4. Drill cores of similar sövite rocks of Okorusu (Oku22, Oku23) and Ondurakorume (On4) have been subjected to different stages of alteration. The Okorusu rocks apparently underwent less alteration and belong to Classes 2 and 3 whereas the Ondurakorume sample belong to Class 4. This difference in alteration state is difficult to account for. It may be that the Okorusu samples escaped alteration or that they crystallized from melts which previously separated a water-rich phase. Such a water-rich phase has been held responsible (Chapter 4) for the extensive feldspathization which occurred at this complex. On the other hand the relative absence of feldspathization at Ondurakorume might be because a water-rich phase had not yet separated from the carbonatite magma at the time of its crystallization. The presence of "excessive" fluids could thus have been responsible for the alteration which the Ondurakorume carbonatites underwent (cf. 4.3.1)

3.4.3.1 Chemical changes during martitization

The oxidation of magnetite by deuteric or weathering agents results in a redistribution of elements similar to that displayed by magnetite which underwent oxidation under magmatic conditions as described by Wright and Lovering (1966). Fig. 36 illustrates that the martite lamellae of Ti-poor magnetite are impoverished in Mn, Mg, V and total Fe but relatively enriched in Ti. No redistribution of Al seems to occur, except for magnetite from sample D366 whose martite lamellae are depleted in this element.

The behaviour of some elements during progressive martitization is further illustrated by magnetite of sample D135 which has been altered into subgrains of various reflectivity. A similar texture has been described by Wilson and Watkins (1967) as due to the formation of maghemite, which, in the presence of

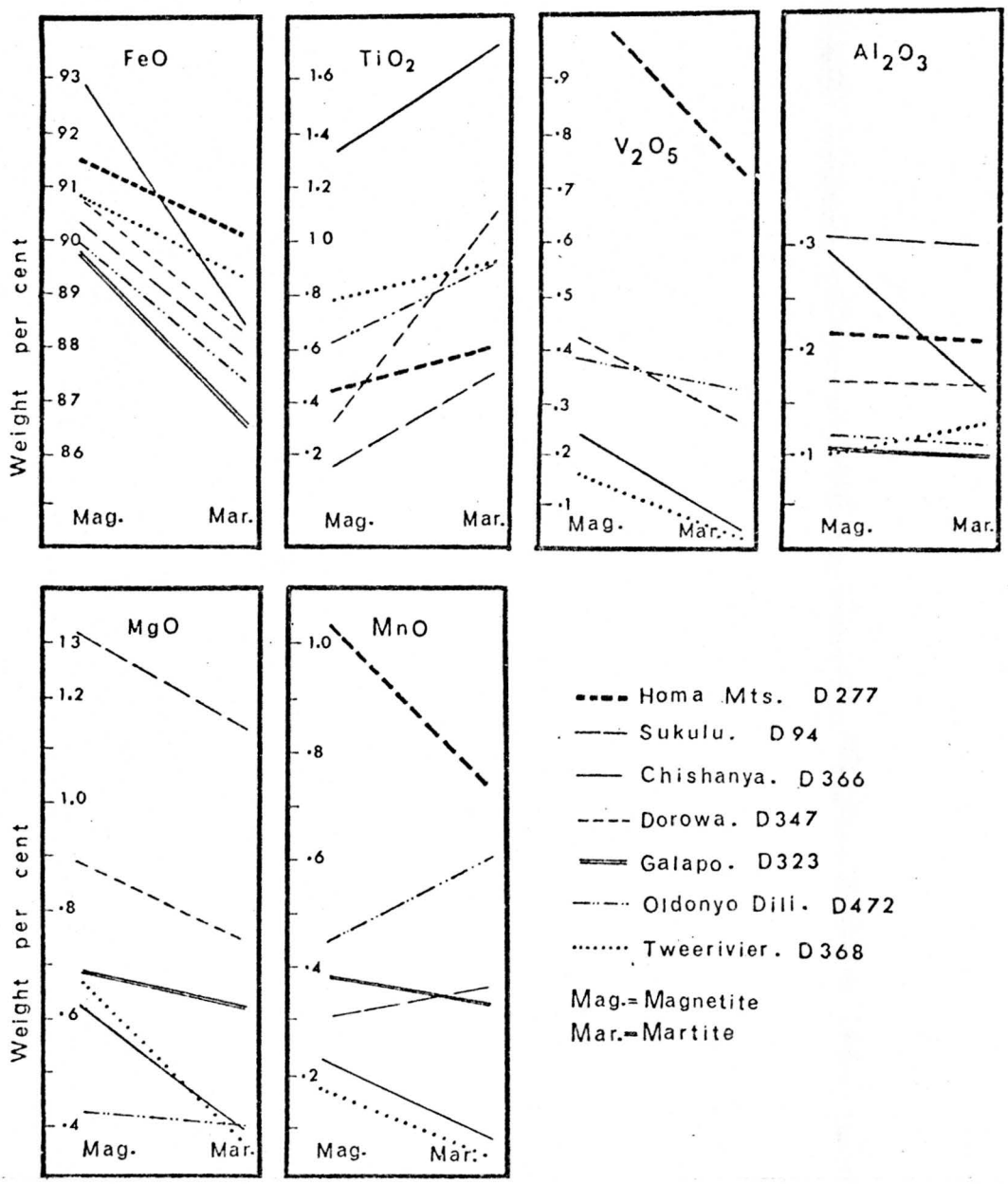


Fig. 36: Chemical changes during martitization of magnetite. Lines connect the composition of unaltered magnetite with that of its martite lamellae. Analyses done by microprobe as described in the Appendix.

water (David and Welch, 1956) and below 600°C (Colombo, et al., 1965) has been found to be the result of oxidation of hematite-free magnetite.

Ten randomly selected microprobe analyses of areas of various reflectivity within the same grain, i.e. different subgrains, were made. (Fig. 35e).

Fig. 35(e): Magnetite oxidized into maghemite(?) subgrains with variable reflectivity. Such a texture has been observed in one specimen only. Its development might be restricted to hematite-free magnetite grains (cf. 3.4.3.1) Toror Hills. Sample D135. (x 250, oil immersion under crossed nicols).

The "normative" hematite content of these subgrains as calculated by Anderson's (1968) scheme, is plotted against their MnO, MgO and Al_2O_3 contents in Fig. 37.

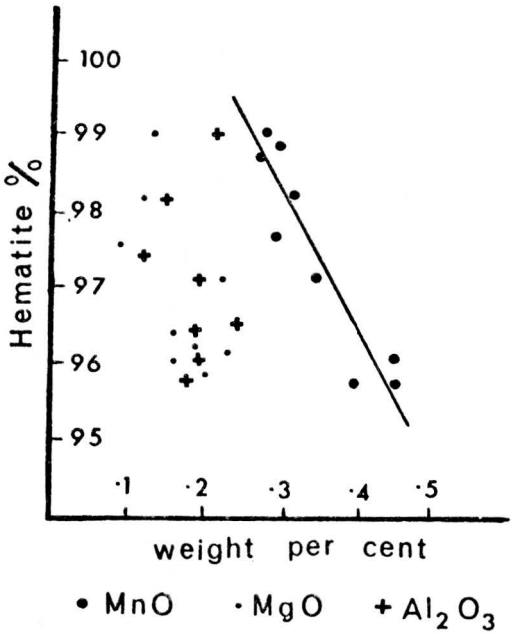


Fig. 37: Microprobe analyses of different areas in a single maghemite grain of sample D135, showing a decrease in MnO and (MgO?) with progressive maghemitization. Per cent hematite obtained by recalculation of the analyses according to Anderson (1968).

MnO and possibly MgO show a depletion with increased martitization which sup=ports the above results. The decrease in these minor elements is ascribed to spinel exsolution which accompanies the martitization. This process takes place at the expense of octahedral Fe^{+2}. This leaves the cation population of tetra=hedral sites constant and vacancies in the octahedral sites which finally results in the collapse of the magnetite structure into that of hematite. The octahe=drally sited Mg and Mn (substituting for Fe^{+2}) have relatively high diffusion capabilities because bonding is more ionic in octahedral sites than in tetrahe=dral ones. These elements would thus readily exsolve as spinel phases during martitization because the hematite structure appears unable to dissolve appre=ciable amounts thereof. Fig. 35 shows the occurrence of spinel phases in the martitzed areas of some of the samples studied. The appearance of exsolved phases during oxidation might be distinctive of magnetite of high Mg, Al, and Ca content. Wright and Lovering (op.cit.) also mentioned the appearance of spinel in hematite lamellae in magnetite from New Zealand black sands which contains about 2 wt% Mg.

CONTENTS

4 METASOMATIC ROCKS

4.1 INTRODUCTION

The wall rocks of alkaline and carbonatite complexes frequently display a particular style of metasomatism in which changes in chemical composition, the development of new minerals and the modification of internal texture are typical. One of the earliest accounts of this type of metasomatism is that of Brögger (1921) who used the term "fenitization" to describe the processes responsible for the alteration of the wall rocks of the Fen alkaline complex. Since then authors such as McKie (1966), Verwoerd (1966), Woolley (1969), Currie and Ferguson (1971), Siemiatkowska and Martin (1975), Vartiainen and Woolley (1976) and Rock (1976) have contributed towards the understanding of the processes involved so that the fenitization of felsic as well as mafic rocks are today reasonably well understood.

The main objectives of most studies concerning fenitic rocks is to determine the chemical and mineralogical changes which occured during their formation as well as the nature and origin of the fluids responsible. Such investigations are very often limited by the fact that the original wall rocks are not available or recognizable and that the magmatic rocks from which these fluids could have originated are not represented on the surface. The fenites of the Okorusu and Kalkfeld complexes are associated with a variety of alkaline as well as carbonate rocks and provide the opportunity to evaluate quantitatively the mass transfer of elements during this type of metasomatism, especially at Okorusu where samples of the original wallrock and its fenitized counterpart can be studied in a single hand specimen (Fig. 38).

Fig. 38(a): Remnants (white) of feldspathic sandstone in massive metasomatic pyroxenite (fenite). Note the pure calcite veins near the hammer.

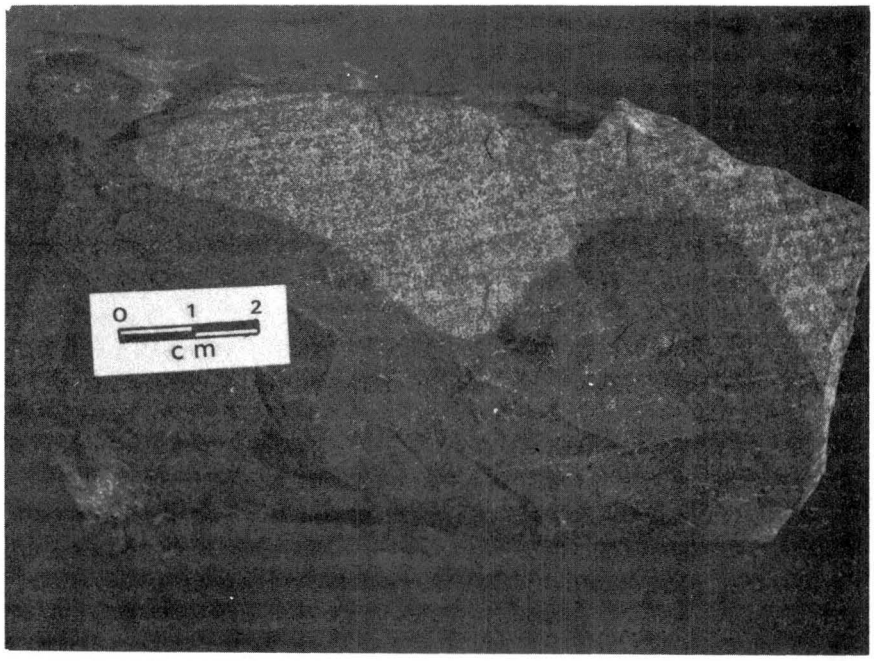


Fig. 38(b): Sharp contact between layered calcareous arkose and massive pyroxenite.

Fig. 38(c): Calcite veins in massive pyroxenite. These veins were regarded by Van Zijl (1962) as of carbonatitic origin. Their chemistry, however, shows no such affinity. It is proposed that they represent sedimentary calcite redistributed during fenitization.

Fig. 38(d): Stages in the transformation of a fenitized calcareous sandstone (1) (note the original laminae) into a feldspar-limonite-carbonate rock (2) and finally into a nearly massive feldspathic rock with minor iron oxides (3).

4.1.1 Present state of knowledge

In broad terms fenitization has been described as a process of sodium and ferric iron metasomatism in which large amounts of Si goes into solution and variable amounts of Al, K and Ca become fixed in the minerals of the metasomatic rocks (McKie, 1966). It seems also that rocks as variable as sandstone, granite, gneiss and amphibolite may be transformed into rocks of an alkali syenitic composition.

No concensus has yet been reached on the nature of the fenitizing fluid. Some recent ideas on their temperature, pressure and composition as well as the magma types with which they were in equilibrium are summarized in Table 4. It is apparent that the origin of fenitizing fluids has been ascribed to alkaline as well as carbonatitic magmas. In some cases these fluids seem to have high K/Na ratios whereas the opposite applies to others. A further complication stems from the fact that some authors (Currie and Ferguson, 1971) believe them to be CO_2-rich with the cations in solution as chloride complexes whilst others (Siemiatkowska and Martin, 1975) favour CO_2-poor fluids with hydroxyl-type complexes. It may well be that various types of fenitizing fluids have been responsible for the metasomatic changes associated with alkaline and carbonatite complexes.

4.2 DESCRIPTION OF METASOMATIC ROCKS

4.2.1 Kalkfeld

Extensive fenitization affected the Salem granite wall rocks as well as the syenitic rocks of this complex. The granites were permeated along small fractures by fluids which caused the replacement of quartz by aegirine-augite and a pale green-blue amphibole. These fluids are also responsible for the turbid appearance of the feldspar. The intensity of the alteration decreases away from the fractures. These fenitization features are more intensively developed near the foyaite which led van Zijl (1962) to suggest that: *"the fenitizing agents became concentrated within the magma during the crystallization of the foyaite."* Feeble signs of fenitization can be found in granite outcrops as far as 4 kilometres from the complex.

The fenitization of the syenite is more difficult to interpret. Large portions have a granular (recrystallized) texture and consist mainly of orthoclase, some-

TABLE 4: Suggested parameters of fenitizing fluids.

Author	Locality	Composition of fenitizing fluid	Tempera= ture	Pressure	Origin of fluid
Woolley (1969)	Chilwa Island Kangankunde	Na, K, CO_2-rich fluid	-	-	Carbonatite magma
Currie and Ferguson (1971)	Callander Bay	Aqueous CO_2 saturated fluid, high Na/K ratio and Si un= dersaturation. KCl/HCl = 30. Cl-rich. $f_{O_2}=10^{-17}$, $f_{S_2}=10^{-11}$ bars	450 - 700°C	few hun= dred bars	Carbonatite magma
Currie and Ferguson (1971)	Callander Bay	NaCl brine (17 molar) Ba:K:H 76:24:0,8 in associa= tion with a low density gas phase	500 - 600°C	500 bars	Carbonatite magma
Vartiainen, H and Woolley, A.R. (1976)	Sokli, Finland	CO_2-rich aqueous fluid with a Na-rich composition that became K-rich at lower temperature.	600 - 700°C	-	Carbonatite magma
Currie (1971)	Brent Crater	K-rich alkaline brine	-	-	Alkaline and/or carbonatite magma
Ferguson, et al. (1975)	Epembe	Aqueous brine with $K/K+Na \approx 0,40$ and Na:K:H ≈ 60:40:1 and Mg, Ca, Fe as mobile compo= nents	450 - 680°C	$P_{H_2O} = P_{tot}$=5kb	Fluid in equili= brium with immis= cible silicate and carbonate magmas
Woolley, et al. (1972)	Borralan Complex	Aqueous fluid with Na > K at high temperature and K > Na at low temperature	-	-	Ultra-potassic magma
Siemiatkowska and Martin (1975)	Nemag and Kusk lakes area	Alkaline fluid poor in Co_2 with Na/K > 1	< 750°C	-	Essexitic or ijolitic magma

times with albite rims or interstitial oligoclase. Other varieties show an irregular development of aegirine-augite as coarse clusters, scattered grains or as thin veins throughout the rock. Processes of feldspathization as well as fenitization may be involved here.

4.2.2 Okorusu

Van Zijl (1962) mapped two major stages of "fenitization" at this complex. The present author suggests that the first stage of pyroxenitization be termed feni= tization whereas the second, i.e. the formation of a brecciated alkali-feldspar= limonite-calcite rock should be referred to as feldspathization.

A variety of sedimentary rock types have been affected by fenitization and were transformed, where the replacement is complete, into a massive alkali pyroxenite. These sedimentary rocks vary in composition from greywacke to calcareous sand= stone, feldspathic sandstone, quartzite and conglomerate. Van Zijl (op.cit.) ascribed the metasomatism to a series of invasions by fluids that became succes= sively more sodium-rich. The banded appearance of some altered calcareous sand= stones is due to alternating layers (1-3 mm thick), consisting of pyroxene and calcite plus quartz. The banding probably reflects the original sedimentary structure (Fig. 38). In some of the greywackes fenitization also resulted in layers of metasomatic pyroxenite alternating with the original constituent bio= tite.

In general it appears that quartz is the first mineral to be replaced, followed in order of susceptibility by feldspar, biotite, calc-silicates and calcite. The formation of pyroxene is usually accompanied by calcite, either as intersti= tial material or as veins in the fractured pyroxenite (Fig. 38). Apatite occurs as large crystals and is invariably associated with calcite which it precedes in crystallization sequence. Pyrite and titano-magnetite are sometimes associated with the apatite. Other metasomatic minerals are biotite and soda-amphibole, formed by replacement of the pyroxene. Feldspar (plagioclase and orthoclase) is occasionally found as remnants of unreplaced primary material but more frequently as large orthoclase (Ab_{25}) crystals which are regarded as products of metasomatism.

After the formation of the metasomatic pyroxenite extensive brecciation occurred around the southern contact of the complex. It was accompanied by a new surge

of metasomatic alteration whereby sedimentary wallrocks, some parts of the pyroxenite and large areas of the syenite ring were transformed into an alkali feldspar-limonite-calcite rock. This metasomatism appears to be similar to that responsible for the occurrence of so-called feldspar fenites, orthosites and feldspathic breccias described from many other carbonatite complexes, e.g. the Chilwa province. These feldspathic rocks were again fractured in some areas and the newly formed cracks filled with almost pure oxidized Fe or Mn ore, or with feldspar, limonite and calcite (Fig. 39a). The metasomatic feldspar is usually turbid owing to minute hematite inclusions, has a maximum ordered structure and a composition which varies between 90 and 95 wt % orthoclase as determined by X-ray diffraction methods.

The characteristic gridiron twinning is absent although patchy domain extinction is present in the larger grains. The associated minerals are limonite and calcite with subordinate amounts of fluorite, quartz, magnetite, siderite, lepidolite and zircon (Van Zijl, op.cit.).

Dykes containing rounded and angular fragments of feldspar set in a fine-grained matrix of feldspar, limonite, calcite and fluorite occur at Okorusu. This mineral assemblage (which is similar to that of the feldspar-breccias) and the abundant flow structures suggest that these dykes represent moblized portions of the feldspathized rocks (Fig. 39b).

4.3 CHEMICAL CHANGES DURING FENITIZATION AND FELDSPATHIZATION

When considering bulk chemical changes during metasomatism it is necessary to compute cationic concentrations in a standard cell, e.g. one based on 100 anions. McKie (1966) has fully argued this case, and showed that from a plot of such concentrations against a parameter indicating the degree of alteration, meaningful conclusions can be made regarding the relative increases of decreases involved. The cationic concentrations per 100 anions of the fenitized and feldspathized rocks of Kalkfeld and Okorusu are given in Table 5. Figs. 40 and 41 have been constructed from these data and the date of Van Zijl (op.cit.) and Verwoerd (1966). Too few analyses of each fenite type are available to justify a statistical evaluation of the gains and losses as advocated by Currie and Ferguson (1971). The various rock types that have been metasomatized at these localities are treated individually in order to eliminate the complications which differences in parental composition would have on the interpretation of the chemical changes.

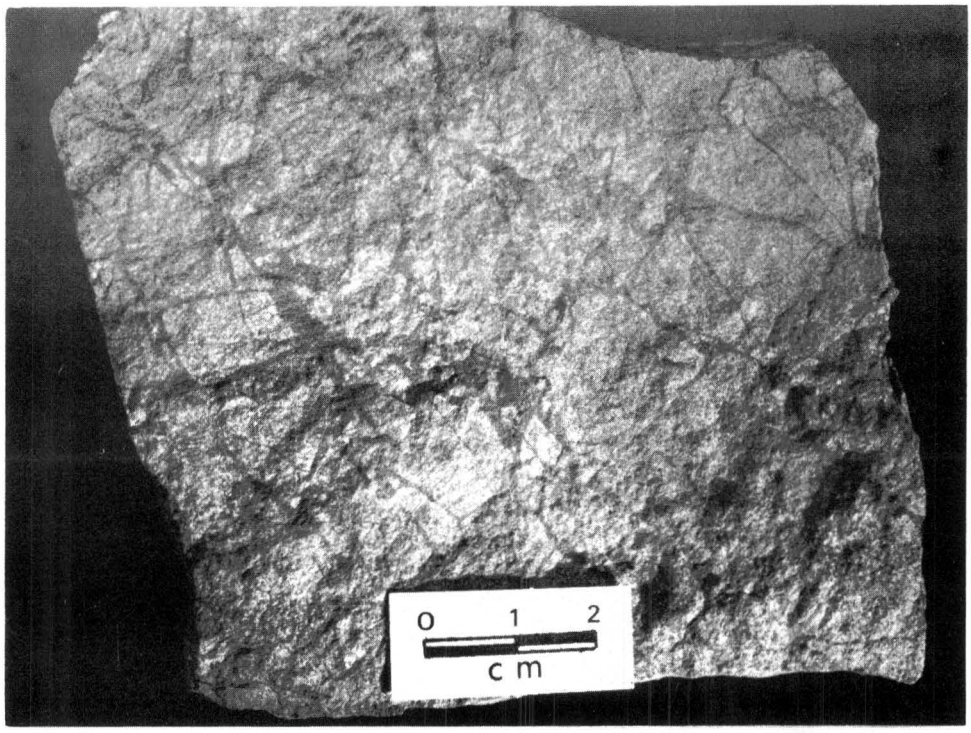


Fig. 39(a): Brecciated and feldspathized pyroxene fenite. The rock consists of feldspar, limonite and calcite with vein fillings of a similar composition.

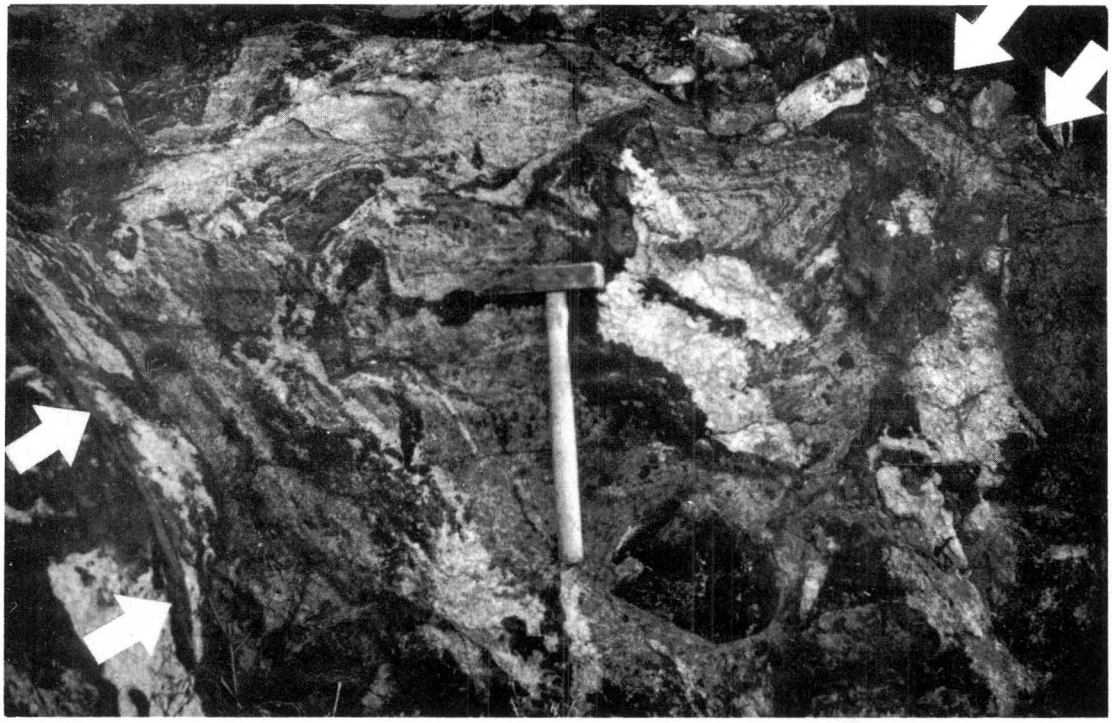


Fig. 39(b): Dyke comprised of angular, rounded and drawn-out fragments of feld= spar rock set in a matrix of feldspar, calcite and iron oxides with irregular flow structure. Arrows indicate the dyke contacts.

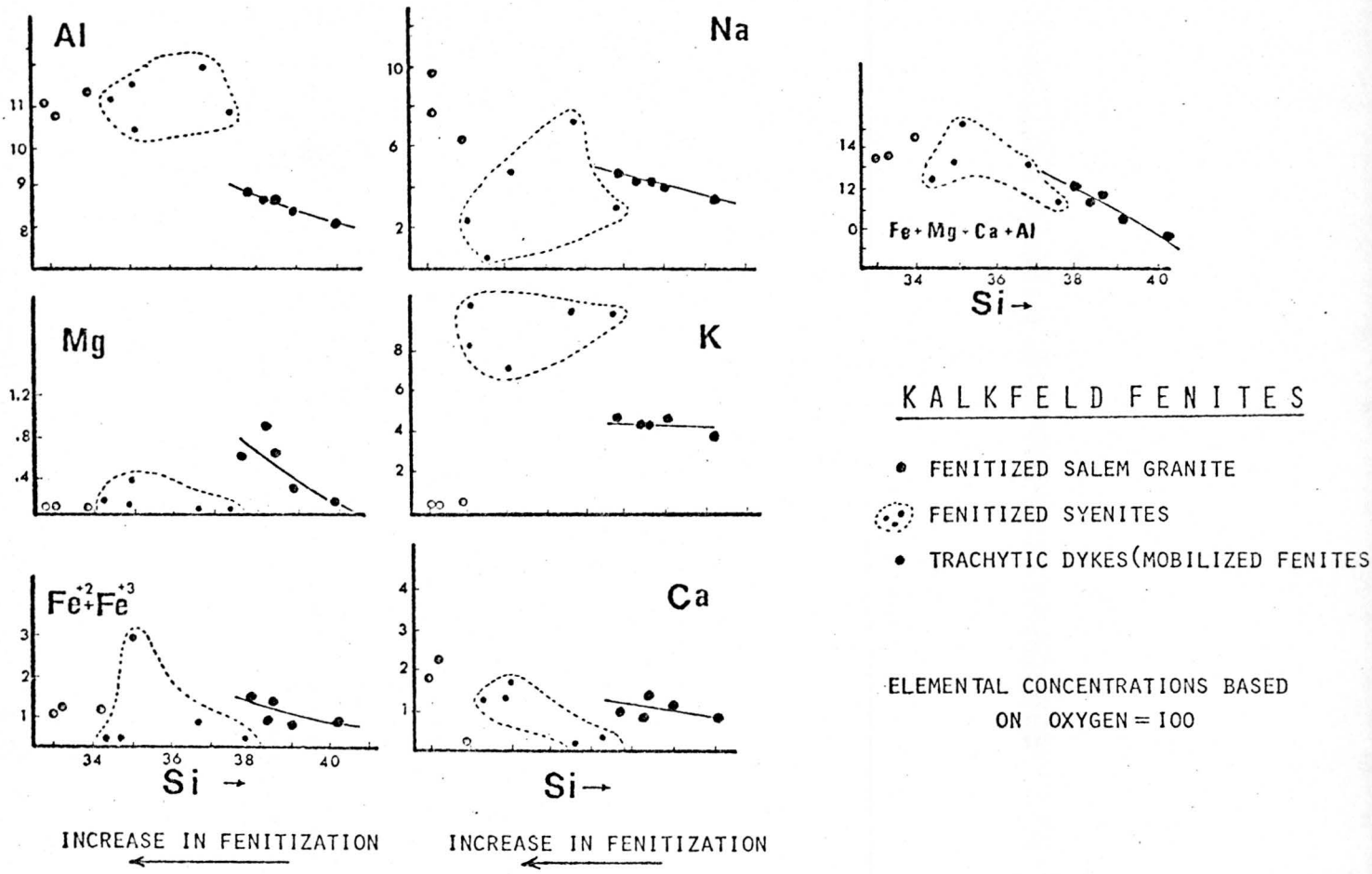


Fig. 40: Variation diagrams of metasomatic rocks from Kalkfeld.

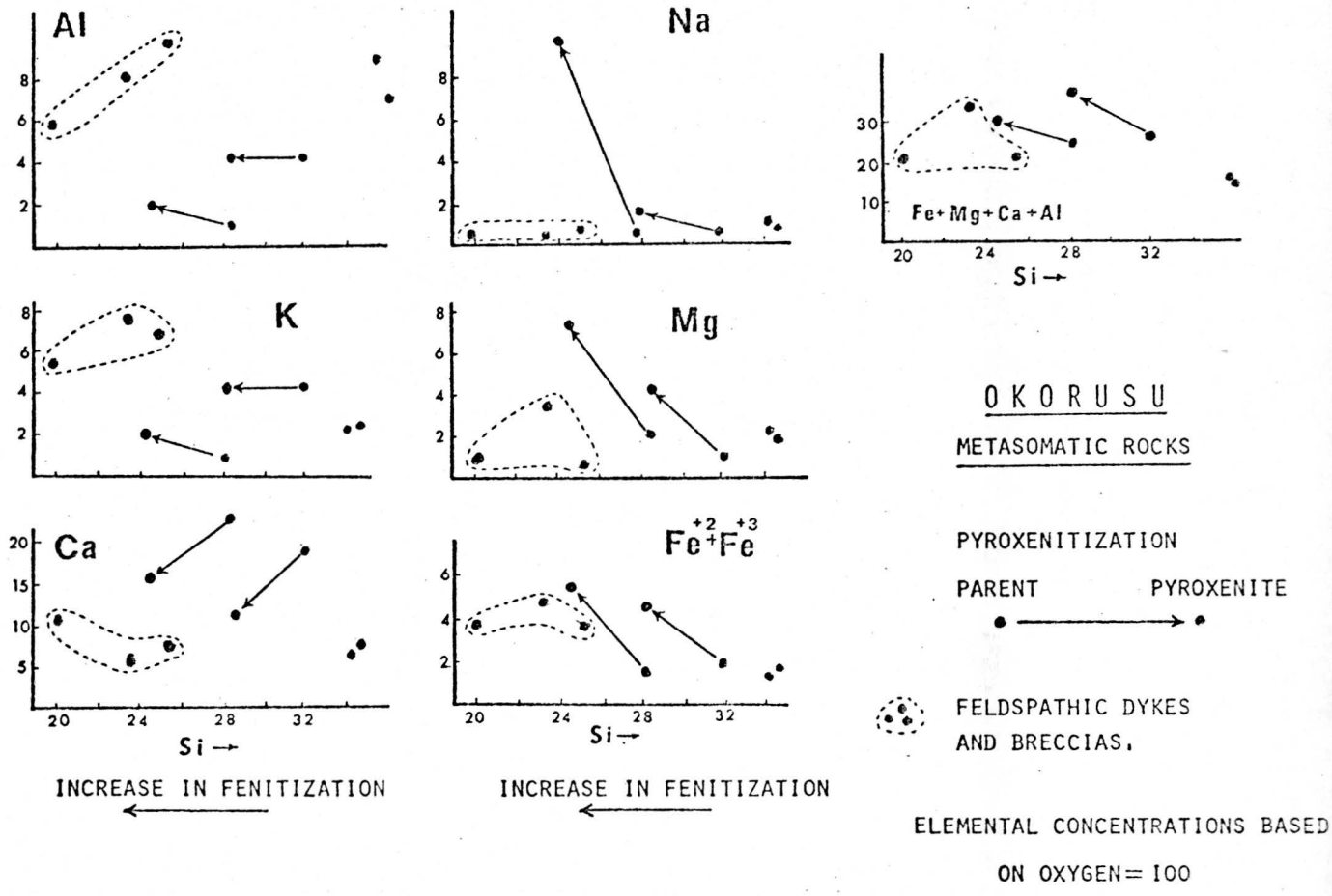


Fig. 41: Variation diagrams metasomatic rocks from Okorusu.

TABLE 5: Composition of fenitized and feldspathized rocks from Kalkfeld in cations per 100 oxygen anions.

	K 17a	K 26	vZ 17	vZ 18	K 85a	K 12	K 10
Si	34,48	38,25	40,12	38,46	37,74	32,97	33,05
Ti	,067	,12	,06	,17	,17	,22	,19
Al	8,16	8,59	8,14	8.52	8,84	11,02	10,74
Fe^{+3}	1,53	,61	,39	,39	1,47	,69	,88
Fe^{+2}	1,12	,44	,26	,66	-	,25	-
Mn	,15	,04	,03	,02	,05	,03	,05
Mg	,96	,84	,08	,53	,51	,08	,05
Ca	3,64	,76	,81	1,33	,93	1,74	2,26
Na	3,88	4,09	3,27	4,05	4,60	7,68	9,56
K	5,28	4,16	3,50	4,14	4,40	2,27	,09
P	,15	,02	,06	,26	,05	,16	,14
C	,82	,55	-	-	-	1,83	2,70

K 17a	fenitized granite
K 26	granite
vZ	fenitized granite
vZ	granite (dark, fine grained)
K 85a	fenitized granite
K 12	trachytic syenite (dyke)
K 10	trachytic syenite (dyke)

	vZ 20	vZ 19	K 18a	K 28	K 4	WJV 50	K 17b
Si	37,73	35,01	36,66	33,97	34,88	33,59	38,95
Ti	,07	,16	,39	,15	,58	1,79	,05
Al	10,97	10,48	12,03	11,38	11,51	11,75	8,44
Fe^{+3}	,21	1,58	,52	,75	,19	,16	,31
Fe^{+2}	,06	,83	,01	-	-	,29	,18
Mn	,01	,01	,01	,05	,01	,01	,01
Mg	,09	,38	,03	,21	,31	,67	,24
Ca	,25	1,59	,19	2,27	1,22	1,76	1,03
Na	2,93	5,02	7,34	,06	1,06	,16	3,98
K	9,57	6,39	4,61	11,32	9,93	2,19	4,32
P	,08	,24	-	-	,17	,48	,01
C	-	4,72	-	3,31	,67	-	,57

vZ 20	fine-grained granulated syenite
vZ 19	medium-grained syenite
K 18a	fenitized syenite
K 28	fenitized syenite xenolith
K 4	coarse grained syenite
WJV 50	orthosite
K 17b	fenitized granite

4.3.1 Kalkfeld

The variations of the major elements with Si (based on a standard cell of 100 anions) of the various fenitic rock types at Kalkfeld are plotted in Fig. 40.

The major elements of the four syenitic samples show no regular variation with Si content. This could be due to original differences in the composition of the rocks analysed or to poor analytical accuracy (in the case of Mg). Also, the chemistry of the syenitic rocks at this complex would probably reflects various stages in the fractionation history of the alkaline magma, various degrees of fenitization and/or feldspathization as well as the difficulty to distinguish magmatic syenite from mobilized fenites. A more detailed study of these rocks is necessary if the chemical changes during their fenitization is to be fully understood.

Fortunately, a study of the relatively homogeneous Salem granite wallrocks and its fenitized counterparts provide sufficient information to arrive at conclusions regarding the origin and composition of the fenitizing fluid. The major elements of these rocks plot on regular trends relative to their Si content. Fig. 40 indicates that Na, Al, Mg and total Fe increased whereas Ca and K remained more or less constant during fenitization. It is of interest that the composition of some analysed trachytoidal syenitic dykes plot at the low Si end on the extension of these trends, except for Mg and K which appear to be extraordinarily low. If their Si and high Na contents are interpreted as the result of a more advanced stage of fenitization it might well be that these dykes represent mobilized (melted) fenitic rocks.

The variation of the major elements as shown by Fig. 40 are not all independent. The sum of Si+Al+Na+Fe(tot.) for the granitic rocks stays virtually constant (51,86-52,19), which suggests that metasomatism occurred essentially through substitutions involving these element only. Si is possibly replaced by Na plus one of Al or Fe in such a way as to preserve charge balance.

Minor occurrences of feldspathization are present at this complex. Sample K28 is of a rock type which respresents a feldspathized xenolith of probable syenitic origin, brought to the surface during the emplacement of the central carbonatite plug. Its chemistry differs significantly (higher K, Ba and trace element content) from that of the previously mentioned fenite types (Table 15).

4.3.2 Okorusu

Six analyses of fenitized sedimentary rocks are presented in Table 6. Plots of the variation in cation versus Si contents of the standard cells of these analyses can not be expected to produce meaningful trends because of the highly variable nature of the original rock compositions. Nevertheless, two analyses of the metasomatic pyroxenite can be coupled with analyses of their parental material (samples obtained from the same hand specimen or outcrop). Their standard cell contents are plottend in Fig. 41 which shows that similar trends pertain to both sets of analyses. The samples with the higher Si content (Oku 33a and Oku 33b) have obviously undergone less fenitization than those of the other set. Furthermore, the general increases are the same as those illustrated by the fenitized granites of Kalkfeld except that Al tends to remain constant and Mg shows a sharper increase at Okorusu.

The composition of samples representing the feldspathization stage at this complex are also plotted in Fig. 41. Two analyses are of the alkali-feldspar-limonite-carbonate breccia whereas a third represents a feldspar-carbonate breccia dyke. These three rocks have similar compositions, suggesting that the breccia dyke could be a remobilized portion of the feldspar breccia. They are poorer in Si than any of the pyroxenite rocks but show a significant increase in Al, K and CO_2.

The carbonatite magma intruded near the centre of the area affected by feldspathization. This suggests a relationship between the fluid responsible for the feldspathization and the carbonatite magma - a suggestion supported by the trace element content of the rocks concerned (section 4.4.3). The nature of the fluid is more problematical but can be estimated by calculating the mass transfer of elements between an unaltered rock and its feldspathized product (cf. 4.4).

4.4 QUANTITATIVE MODELS FOR THE METASOMATIC PROCESSES

At Okorusu the massive pyroxene fenite was formed in such a way that in certain outcrops the original sedimentary rock as well as its fenitized product can be sampled (Fig. 38). At a later stage the same rocks have, furthermore, been affected by feldspathization. It is thus possible to study the mineralogical and chemical changes which accompanied these two major stages of metasomatism with a prior knowledge of the composition of the parental material. Such a case

TABLE 6: Composition of fenitized and feldspathized rocks from Okorusu in cations per 100 oxygen anions.

	Oku 33b	Oku 33a	vZ 11	Oku 34	Oku 35	Oku 37	vZ 14	vZ 15	Oku 36
Si	31,64	28,18	24,25	35,69	35,24	28,22	18,97	25,11	23,43
Ti	,15	,14	tr	,33	,33	,15	,31	,65	,17
Al	3,92	3,85	1,32	6,67	8,70	3,54	5,19	9,27	7,80
Fe^{+3}	,98	2,41	2,21	1,33	,22	1,10	3,71	3,63	4,64
Fe^{+2}	,75	2,17	2,99	,67	,14	,15	-	-	-
Mn	,37	,36	-	,07	,03	,15	,18	,08	,18
Mg	1,10	4,33	7,30	2,00	2,28	2,27	,65	,04	3,42
Ca	19,13	11,92	15,28	3,33	4,24	28,41	10,63	7,53	6,24
Na	,29	1,44	10,63	5,33	3,26	tr	,10	,56	,16
K	3,67	3,61	1,33	2,00	1,96	tr	5,12	6,31	7,37
P	,08	,57	tr	,08	,05	,06	,35	1,35	,12
C	2,17	2,48	4,31	2,24	1,63	2,27	5,26	4,83	9,08

Oku 33b	fenitized feldspathic sandstone	Oku 37	feldspathic quartzite
Oku 33a	pyroxene fenite	vZ 14	feldspathic breccia
vZ 11	pyroxene fenite	vZ 15	feldspathic diatreme (dyke)
Oku 34	fenitized feldspathic sandstone	Oku 36	feldspathic breccia
Oku 35	fenitized feldspathic sandstone		

lends itself ideally to application of the composition-volume equation developed by Gresens (1967) for the study of metasomatic processes. This approach was used by Babcock (1973) in a study of granitization in the Stavanger area, Norway, but has not yet been applied to fenitized rocks. An important advantage of this method is that volume changes can be taken into account.

Babcock (op.cit) showed that the magnitude of chemical transfer for any given component in a metasomatic system can be expressed as follows:

$$X_n = b(X_n) - a(X_n) \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

where:

a = weight of parent rock A in gram, b = weight of product rock B in gram.

X_n = weight fraction of chemical component n in rock B

X_n = weight fraction of chemical component n in rock A

substituting terms for volume change and density, equation (1) can be rewritten as:

$$\Delta X_n = a \left[(K_v X_n^{\beta} \frac{\rho^{\beta}}{\rho^{\alpha}} - X_n^{\alpha} \right]$$

where:

ΔX_n = the chemical transfer (expressed in weight per cent when a is arbitrarily designated as 100 grams) of component n between phases A and B.

K_v = ratio between the final and initial volume of the rock mass.

ρ^{α} = density of parent rock.

ρ^{β} = density of product rock.

4.4.1 Mass transfer during fenitization at Okurusu

The formation of the pyroxene fenite occurred without any volume increase as no brecciation can be seen in the samples analysed and because traces of the original sedimentary structure can be followed without discontinuity from unaltered portions of the parent rock into the metasomatic product (Fig. 38b). The composition-colume equation during the formation of the pyroxenite as represented by samples K33a and K33b. K_v was assumed as 1 and the data obtained used to construct Fig. 42. It is evident that Fe_2O_3, MgO, Na_2O and P_2O_5 are the main components that were added, that K_2O, MnO, Al_2O_3 and TiO_2 remained constant whereas little SiO_2 and a considerable amount of CaO was removed or redistributed during this phase of metasomatism. These trends differ from those obtained through the

conventional approach of McKie (see section 4.3) in that it indicates a more significant removal of Ca and a near constancy in Al, Si and K.

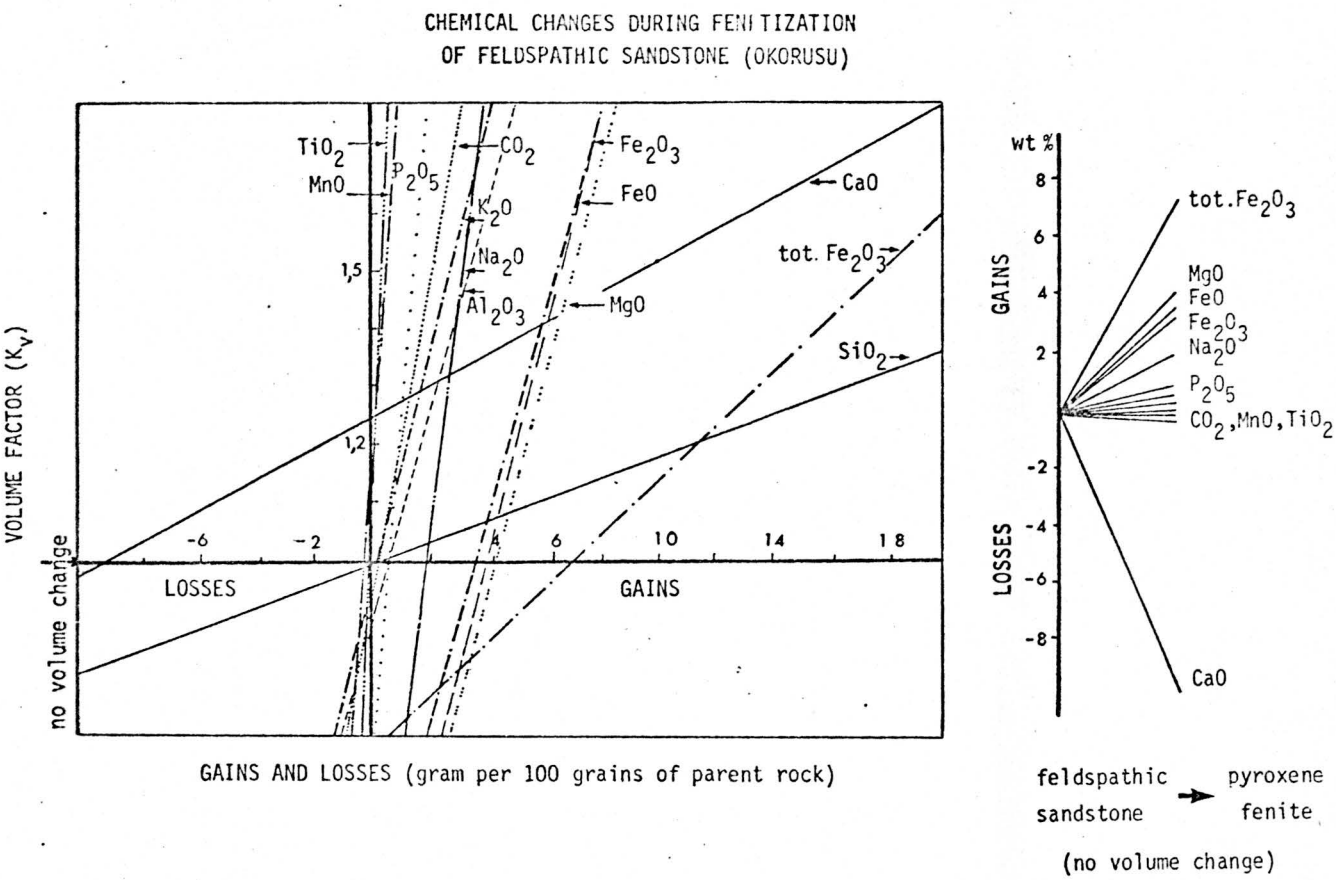


Fig. 42: Composition-volume diagram for the transformation of a feldspathic sandstone (Oku 33a) into a metasomatic pyroxenite (Oku 33b).

The constancy of SiO_2 during this alteration contrasts with the desilication reactions normally suggested as the dominant processes during fenitization (Currie, 1973). It is believed that the degree of Si-saturation of the fluid (i.e. the chemical potential of Si) relative to that of the invaded rocks controls the extent of desilication. Thus the SiO_2 content of oversaturated granitic rocks at Kalkfeld (≈ 70 wt %) was lowered whereas that of the calcareous and feldspathic sandstones at Okorusu (≈ 52 wt %) remained unaffected.

If the relative increases in Na_2O, Fe_2O_3 (total), MgO and P_2O_5 (Table 6) which took place during the formation of the pyroxenite give an indication of the relative concentrations of these elements in the fenitizing fluid, we find that they must have been present (on a molecular basis) in a ratio of roughly 30:25:40:5.

The mineralogical changes which occurred during fenitization are exemplified by the equations below. They incorporate the added elements in relative amounts similar to the ratio deduced above from the composition-volume calcu= lations and require no change in the Si and Al content.

$$\underset{\text{anorthite}}{2CaAlSi_2O_8} + \underset{\text{quartz}}{8SiO_2} + \underset{\text{elements added}}{5Fe^{3+} + 4Na^{+} + Mg^{2+} + 4H_2O} \Longrightarrow$$

$$\underset{\text{aegirine-augite}}{Na_2Ca,\ Fe_2^{3+},\ Mg^{2+},\ Si_6O_{18}} + \underset{\text{albite}}{2NaAlSi_3O_8} + \underset{\text{magne= tite}}{Fe_3O_4} + \underset{\text{elements removed}}{Ca^{2+} + 8H^{+}}$$

$$\underset{\text{biotite}}{K_2Fe_6(Si_6Al_2O_{20})(OH)_4} + \underset{\text{calcite}}{5CaCO_3} + \underset{\text{quartz}}{12SiO_2} + \underset{\text{elements added}}{3Fe^{3+} + 6Na^{+} + 3PO_4^{3-} + 4H_2O} \Longrightarrow$$

$$\underset{\text{apatite}}{Ca_5(PO_4)_3(OH)} + \underset{\text{acmite}}{6NaFeSi_2O_6} + \underset{\text{orthoclase}}{2KAlSi_3O_8} + \underset{\text{magne= tite}}{Fe_3O_4} + \underset{\text{elements removed}}{5CO_2 + 11H^{+}}$$

The Ca and CO_2 which appear to be in excess in the above equations could account for the frequent occurrence of calcite as interstitial patches or as conspicuous veins in the metasomatic pyroxenite. These veins sometimes merge into irregular coarse-grained bodies which Van Zijl (1962) believed to be of carbonatitic origin (Fig. 38c). However, large differences exist between the trace element content of these carbonate veins and that of the carbonatite proper at this complex (Table 7).

Table 7: Comparison of the trace element content in (ppm) of calcite veins in the pyroxene fenite and the carbonatite at Okorusu.

Rock type	Calcite veins in pyroxene fenite	carbonatite proper		
Sample No.	Oku 42	Oku 40	Oku 6	Oku 12
Nb	10	1203	1961	203
Zr	441	1824	50	7
Y	20	101	64	23
Sr	590	11174	9866	412
Rb	1	2	60	8

It is therefore considered most likely that the calcite of the veins was liberated from the country rock during fenitization.

4.4.1.1 Composition of the fenitizing fluid

The similarity in the chemical trends exhibited by the fenitic rocks of Kalkfeld and Okorusu suggests that the fenitizing fluids which developed at these complexes could have been of a similar composition. In such a case these fluids probably were:

(1) saturated in Si relative to the calcareous sandstone but undersaturated relative to granitic rocks,
(2) enriched in Fe, Na, Mg and P,
(3) highly undersaturated in Ca and probably in CO_2 and
(4) of an oxidizing nature.

Various authors (Currie and Ferguson, 1971; Siemiatkowska and Martin, 1975) have proposed similar compositions for fenitizing fluids from other areas, except for the relatively high P content suggested here. Fluid inclusion work (Rankin and Le Bas, 1973; 1974) indicates that $NaHCO_3$ is a principal component of the original fluids from which ijolites and carbonatites crystallized and that potassium is a relatively minor constituent. This lends support to the proposed composition of the fenitizing fluids associated with the Damaraland complexes.

Serious doubt has been expressed by Siemiatkowska and Martin (op.cit.) on the idea that the fenitizing solutions at Callander Bay were Cl-rich (Currie and Ferguson, op.cit.). The former authors considered that a CO_2-poor fluid, coexisting with an ijolitic magma and in which Na and Fe were transported as alkali-hydroxide complexes, was responsible for the Nemag Lake fenites. So far not much evidence has been put forward to support either of the two ideas. Data on the Cl content of fenitic rocks are lacking and would probably be difficult to interpret. One would expect the chloride content of fenites to be anomalous or at least to show a correlation with their Fe content if the introduced elements, such as Fe, were transported as chloride complexes. No such correlation appears to exist in the Damaraland province (Fig. 43). The Na-Fe fenites of Okorusu and Kalkfeld have among the lowest chloride contents of all the rock types present (except the carbonatites). It thus appears unlikely that the fluids responsible for the Na-Fe fenitization at these two complexes were chloride-rich.

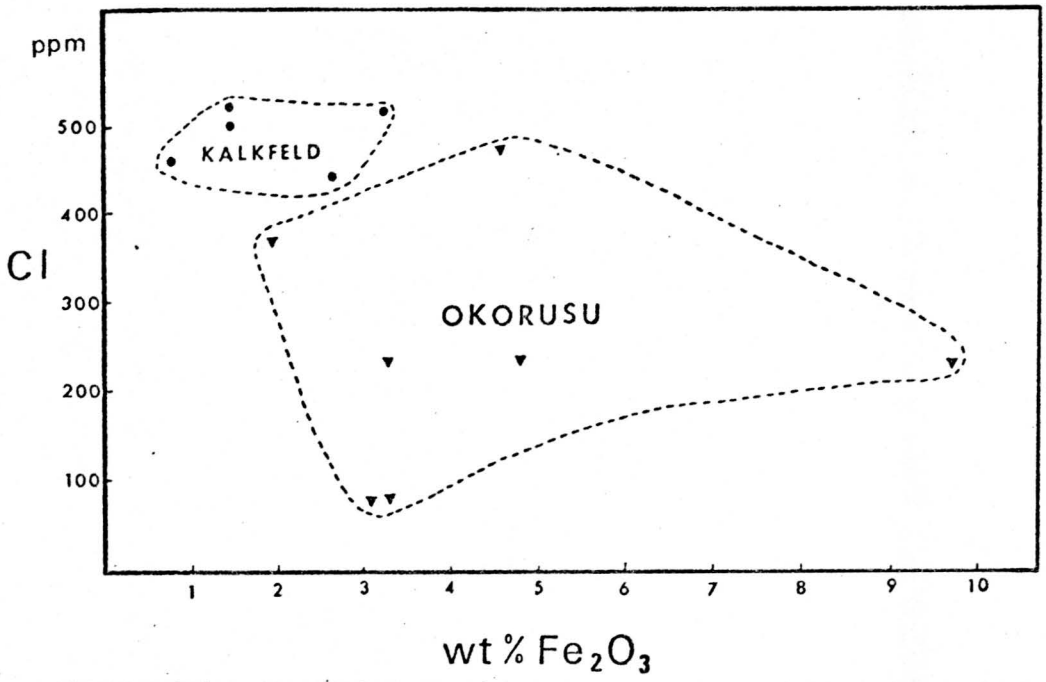


Fig. 43: Variation of the Cl with total Fe_2O_3 content of fenitized rocks from Kalkfeld and Okorusu.

Experimental evidence that may be compared with natural fenitizing systems is scanty. Unpublished data of Martin (1970, in Siemiatkowska and Martin, op.cit.) on the system Na_2SiO_5 - Fe_2O_3 - H_2O showed that Fe^{3+} is transported either as an alkali-hydroxyl or alkali-soluble silicate-type complex and that it precipitates as aegirine down the temperature gradient. Martin and Piwinskii (1968) evaluated the role of Cl^- and other anions in the transport of Fe during the formation of hematite deposits and found no link between the amount of Fe transported and the presence of Cl in the fluid. Thus there is no need to postulate Cl-rich fenitizing fluids in association with the Damaraland carbonatites. It is suggested, in stead, that a gaseous fluid in equilibrium with an alkaline magma and in which alkali and metal ions were transported as hydroxyl complexes caused the extensive pyroxene fenitization observed.

4.4.1.2 Temperature of fenitization

The temperature of fenitization at Kalkfeld and Okorusu is limited by the stability of K-feldspar and aegirine. An upper temperature limit of 500°C for the coexistance of K-rich feldspar (Or = 80 wt %) and aegirine at 1,25 Kbar in the

presence of peralkaline fluids is proposed by Luth, et al. (1973). The pyroxene fenites of Okorusu contain sporadic grains of homogeneous alkali feldspar with a composition, as determined by X-ray diffraction, that varies between 85 and 93 wt % Or. This composition suggests a maximum temperature of about 600°C (at 1 Kbar water-vapour pressure) on the potassic limb of the solvus curves of Smith and Parsons (1974).

Orthoclase, albite and aegirine-augite from the fenitized granite surrounding the Kalkfeld complex were analysed with the electron microprobe. These analyses (Table 8) confirm the endmember composition of the feldspars and the Fe-Ca-Na-rich nature of the pyroxene. The fenitization process therefore probably took place at a temperature below 500°C according to the data of Luth et al. (1973).

Tabel 8: Microprobe analyses of minerals from fenitized granite, Kalkfeld.

	Orthoclase	Albite	Aegirine-augite
SiO_2	65,3	67,54	51,56
TiO_2	-	-	,68
Al_2O_3	17,8	18,73	,26
FeO	-	-	21,59
MnO	-	-	-
MgO	-	-	4,11
CaO	-	-	14,28
Na_2O	1,45	11,41	6,42
K_2O	16,32	,20	-
	100,68	97,88	98,90

4.4.2 Mass transfer during feldspathization at Okorusu

Samples Oku 32a and Oku 36 represent a pyroxenite and its feldspathized equivalent respectively. The compositional variations versus volume changes (Kv) for the conversion of Oku 32a to Oku 36 have been calculated, using the Gresens equation (page 94) and are plotted in Fig. 44.

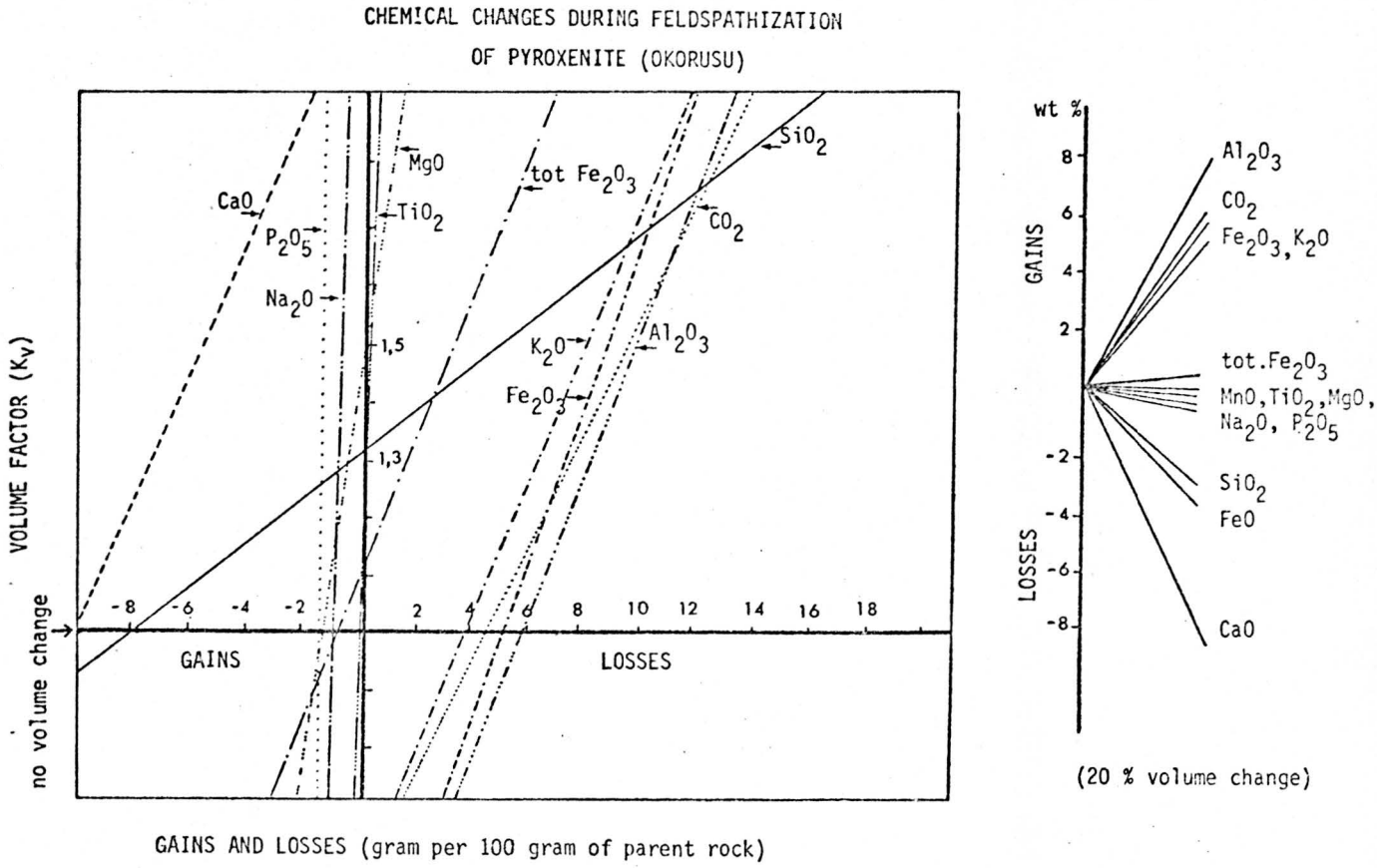


Fig. 44: Composition-volume diagram for the transformation of the pyroxenite (Oku 33b) into a feldspar breccia (Oku 36).

As brecciation and fracture filling form prominent features of the feldspathized rocks (Fig. 39a) a 20% volume increase seems reasonable. Assuming such an increase in volume we find that elements such as total Fe, Ti, Mg, Na and P remained constant whereas Al, K and CO_2 increased significantly with a concommitant removal of Si and some Ca (Fig. 44). Feldspathization is usually accompanied by desilication (Woolley, 1969) and in this case also with a depletion in Ca. The removal of these elements is probably due to the fact that the fluids were undersaturated in these elements relative to their concentration in the original pyroxenite. However, they were not totally removed from the system but were apparently redeposited as chalcedony and calcite in veins and breccia fillings in some of the feldspathized rocks. Calcium could also have combined with fluorine from the fluid to form the disseminated fluorite which occurs in variable amounts in most of the feldspathized rocks.

The following equations represent some of the mineralogical changes which occurred during the feldspathization of a partly fenitized calcareous sandstone (Fig.38d) and show that an introduction of ions in the proportion $4Al^{3+} : 2K^{+} : 8CO_3^{2-} : 8OH^{-}$ is required for this transformation. When recalculated into oxide proportions the ratios are $7{,}5Al_2O_3 : 2{,}5K_2O : 8CO_3^{2-} : 8{,}5H_2O$ which corresponds roughly with the relative composition gains as obtained by the composition-volume equation of Gresens (Fig. 44).

$$\underbrace{(Na_2Ca)(Fe_2^{3+},Mg^{2+})Si_6O_{18}}_{\text{aegirine-augite}} + \underbrace{6SiO_2 + 3Fe_3O_4}_{\text{quartz magnetite}} + \underbrace{4Al^{3+} + 2K^{+} + 8CO_2 + 8OH^{-}}_{\text{elements added}} \Longrightarrow$$

(aegirine-augite: partly fenitized sandstone)

$$\underbrace{2NaAlSi_3O_8}_{\text{albite}} + \underbrace{2KAlSi_3O_8}_{\text{orthoclase}} + \underbrace{5FeOOH}_{\text{limonite}} + \underbrace{6FeCO_3 + CaCO_3 + MgCO_3}_{\text{Fe/Ca/Mg carbonates}} + 3H^{+}$$

Another equation, using representative mineral assemblages and the same relative proportions of added elements may account for the loss in Mg and Si as calculated by the composition-volume equation.

$$\underbrace{(Na_2Ca)(Fe_2Mg)Si_6O_{18}}_{\text{aegirine-augite}} + \underbrace{2CaCO_3 + 7SiO_2}_{\text{calcite quartz}} + \underbrace{4Al^{3+} + 2K^{+}}_{\text{elements added}} \Longrightarrow$$

(aegirine-augite, calcite, quartz: partly fenitized calcareous sandstone)

$$\underbrace{2KAlSi_3O_8}_{\text{orthoclase}} + \underbrace{2NaAlSi_3O_8}_{\text{albite}} + \underbrace{2FeCO_3}_{\text{siderite}} + \underbrace{Si^{4+} + Mg^{2+} + 3Ca^{2+}}_{\text{elements removed}}$$

A combination of these reactions account more realistically for the observed changes in chemistry and mineralogy which occured during the feldspathization process as illustrated in Fig.38d.

4.4.2.1 Composition of the feldspathizing fluid

The chemistry of the feldspathization processes, as discussed above, suggests that the solutions were:

(i) very undersaturated in Si;
(ii) oversaturated in K,Al and CO_2;
(iii) did not introduce significant amounts of Fe, Mg, Ti and P;
(iv) removed Si, Ca and Mg during the process, and
(v) were highly oxidizing.

Since Burnham (1967) showed that solutions which are undersaturated in SiO_2 can not be in equilibrium with rocks or magmas saturated with SiO_2 the carbonatite magma seems the most likely source for these metasomatic fluids. This author also emphasized that Fe, Ca and Mg are mobile only if moderate to high concentration of certain anions are present. The abnormally high F and Cl contents of the feldspathic rock suggest that the fluids responsible for this metasomatism were enriched in these elements. According to Burnham (op.cit.) F has no effect on the mobility of these elements so that Cl appears to be the ion involved. It is thus suggested that the elements introduced were probably transported as chloride complexes. This contrasts with the low Cl content suggested for the fluids responsible for the earlier aegirinization process. The carbonatitic rocks are extremely depleted in Cl, a feature probably due to the large scale extraction of this element from the carbonatitic magma into its associated fluid phase.

Most of the described occurrences of feldspathization (Currie, 1971; Jacobsen and McCarthy, 1975) are apparently associated with an increase in Al whereas during Na-fenitization (McKie, 1966; Currie and Ferguson, 1973; Siemiatkowska and Martin, 1975; Vartiainen and Woolley, 1976) Al seems to have remained constant or was slightly depleted. It thus appears likely that the fluids derived from carbonatitic magmas are rich in Al and K and that, as deduced from the mass transfer calculations, the Al:K ratio approaches 2:1. It is surprising that during the transformation of the pyroxenite into the feldspar-limonite-calcite rock very little Fe and no Mg or P were introduced. Although these elements are relatively abundant in carbonatite environments they are apparently not concentrated in the associated high temperature fluid phase. They remain in the carbonate magma in stead, accumulate in the lower temperature fractions and, ultimately, are enriched in a hydrothermal phase. The presence of hematite and fluorite deposits as well as the thin late stage apatite veins at these complexes supports this idea. Although it is possible to distinguish the high and low temperature fluids by their chemical effects, the transition is likely to be a gradational one.

4.4.2.2 Temperature of the fluid

The alkali feldspar which developed during this stage of metasomatism is of a maximum ordered type. Its composition, patchy development and turbid appearance are similar to those of other occurrences (Heinrich and Moore, 1970). The samples investigated show the development of one alkali-feldspar only, so that an estimate of their temperature of formation by applying the Barth feldspar thermometer is impossible.

It has been suggested earlier that the feldspar-trachyte dykes probably represent feldspar-breccia mobilized from a deeper level. A formation temperature of up to 700°C has been suggested by Von Eckermann (1948) for similar phenomena at the Älno Complex. On the other hand, hydrated iron minerals and fluorite are associated with the felspathization, indicating a much lower temperature. The temperatures involved therefore seem to range from that of anatexis (≈ 700°C, probably at deeper levels and nearer to the source) to that of a hydrothermal fluid (around 200°C) during its waning phases. Temperatures deduced for the feldspathization associated with carbonatites, e.g. Currie and Ferguson (1971) are surely dependent on the mineral assemblages exposed at a particular level of erosion and obviously do not reflect the whole temperature range over which these fluid were active. (In view of the wide stability range of acmite, this state of affairs probably applies to the earlier pyroxene fenitization process as well).

4.4.3 Trace element transfer

Little information is available on the behaviour of trace elements during alkali metasomatism. Heinrich (1966) mentions a few occurrences characterized by an increase in Nb, Ba, and some of the rare earth elements during fenitization. At some of these localities elements such as Sr, Ti, F, Be, Ti, Zr and V were also introduced. Curry (1971) and Ferguson, et al. (1975) published trace element data on the Brent Crater and Epembe fenites respectively. These authors showed that Ba, Sr, Ti and Nb tend to increase during fenitization and that a degree of covariance exists between Ca and Sr as well as between Nb and Ti. However, the variable nature of the parental rocks tended to obscure the results.

Vartiainen and Woolley(1976) presented data on the behaviour of Y, Zn, Ni, Cr, Cu, V, Zr, Nb, Li, Rb, Sr and Ba during the fenitization and feldspathization of the

wall rocks of the Sokli carbonatite. Although the variable nature of the wall-rocks again proved troublesome they established that Nb and Ba were introduced during the Na-stage as well as the K-stage of metasomatism.

The metasomatic rocks of the Okorusu and Kalkfeld complexes display similar co-variant relationships between Rb and K_2O and between Sr and CaO (Fig. 45). They also show the expected increase in Sr and Nb and suggest that enrichment in these elements occured mainly during pyroxene fenitization (Fig. 46). Although the feldspathic breccias have high Sr and Nb concentrations they do not show a significant increase above Sr and Nb of the pyroxene fenites.

Feldspathization, on the other hand, increased the Ba, Cl, F and rare earth element contents of the initial parental rocks. The concentrations of these elements in the Okorusu sedimentary rocks as well as the Kalkfeld granites are similar to those of their fenitized products but the feldspar breccias are highly enriched in these elements. Although the rare earth elements are relatively enriched in the feldspathized rocks the behaviour of individual REE differs slightly as far as pyroxenitization and feldspathization are concerned. Ce is enriched in the pyroxene fenites whereas La concentrates in the feldspathized rocks (Fig. 47).

The rare earth element contents of the alkaline rocks of Kalkfeld and Okorusu show a somewhat anomalous behaviour when plotted against differentiation index. Increasing concentrations of elements such as Rb, Ba, Th, Y and the rare earths are to be expected during the crystallization of alkaline magmas (Nockolds and Allen, 1954, 1956). The concentration of Y, Ce, La and Nd in the Okorusu alkaline rocks is nearly constant with a slight decrease in rocks with high differentiation indices. The Kalkfeld rocks also show a marked decrease with differentiation (Fig. 48b). This might suggest that these trace elements have been lost from the alkaline magmas during their crystallization. The obvious suggestion is that they fractionated into a gaseous/fluid phase which caused the fenitization associated with these complexes. The Rb, Sr, Nb, Y and REE contents of the pyroxene fenite at Okorusu and the fenitized granites and syenites at Kalkfeld are quite similar to those of their associated, and specifically early, alkaline rocks (Figs. 48a and b). This feature supports the idea that the pyroxenitization was caused by a fluid in equilibrium with the ijolite-nepheline syenite magmas and thus not associated with the carbonatitic magmas. On the other hand, the feldspathic breccias have trace element contents which correspond to those of the associated carbonatitic rocks (Fig. 48a) which suggests

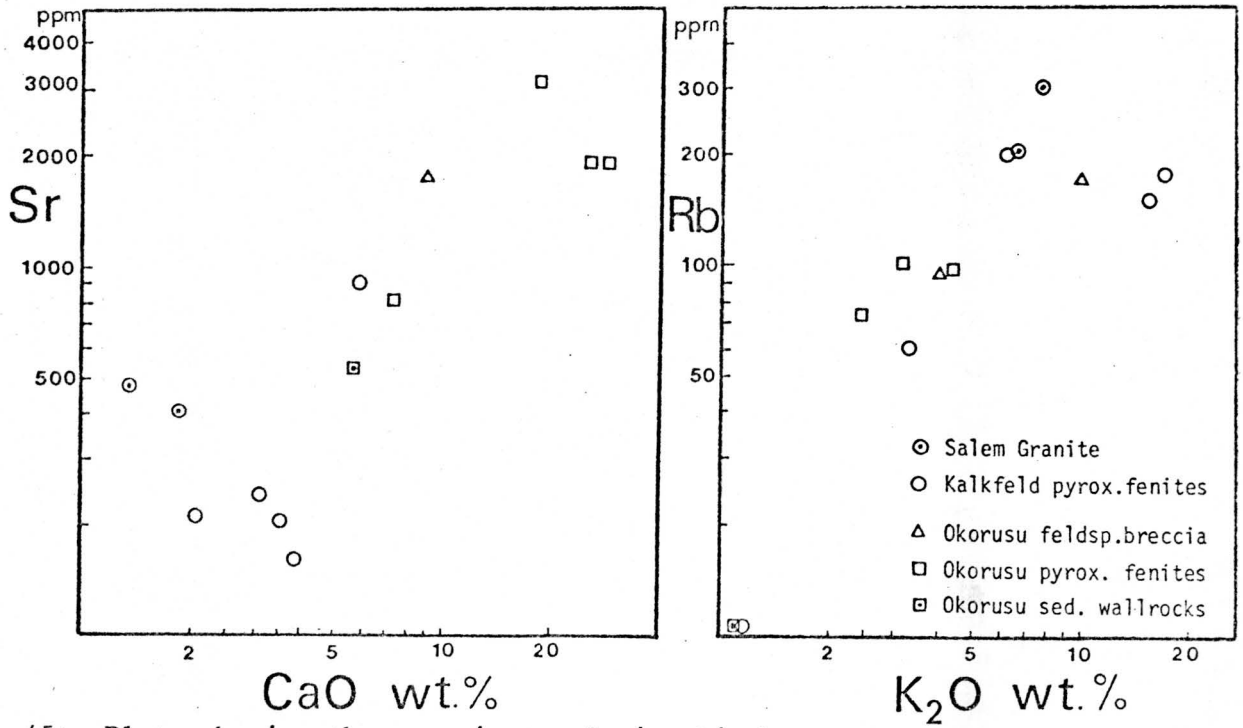


Fig. 45: Plots showing the covariant relationship between Sr and CaO and between Rb and K_2O contents of the Kalkfeld and Okorusu metasomatic rocks.

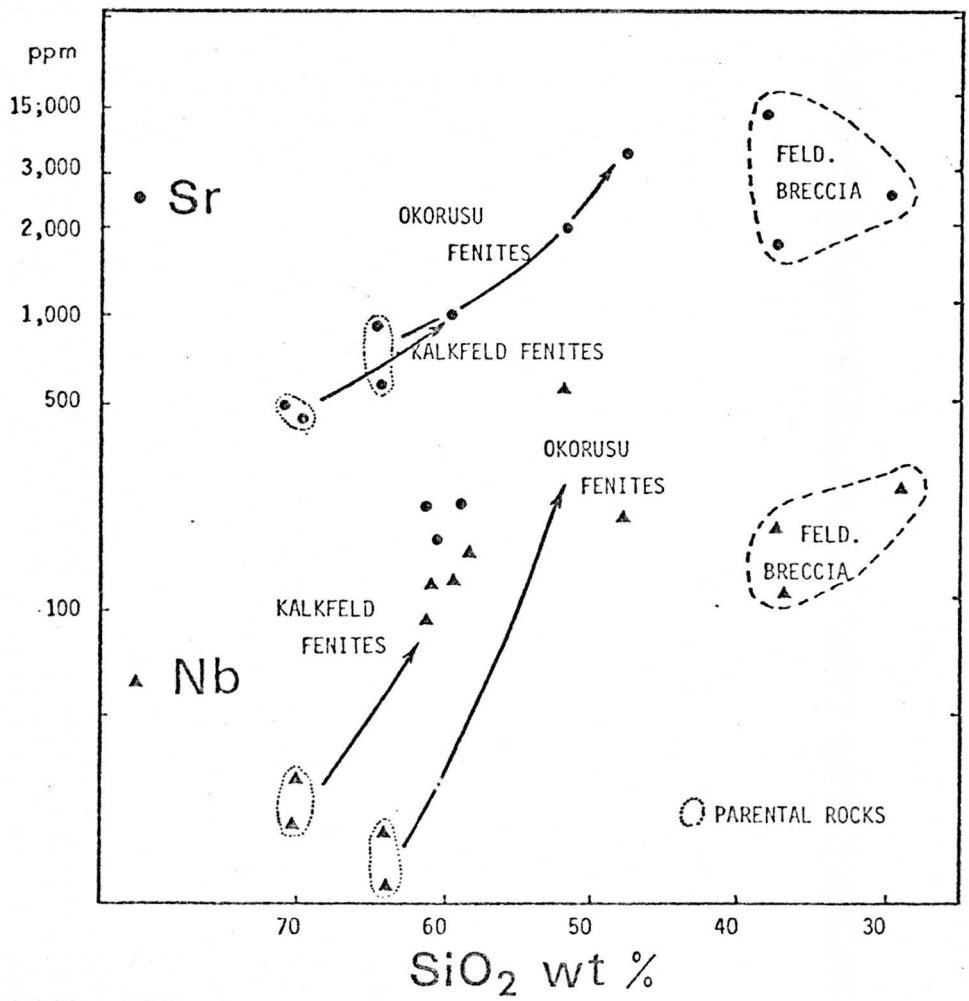


Fig. 46: Plot illustrating the increase in Sr and Nb with fenitization. Note that the subsequent feldspathization did not affect the Sr and Nb contents significantly.

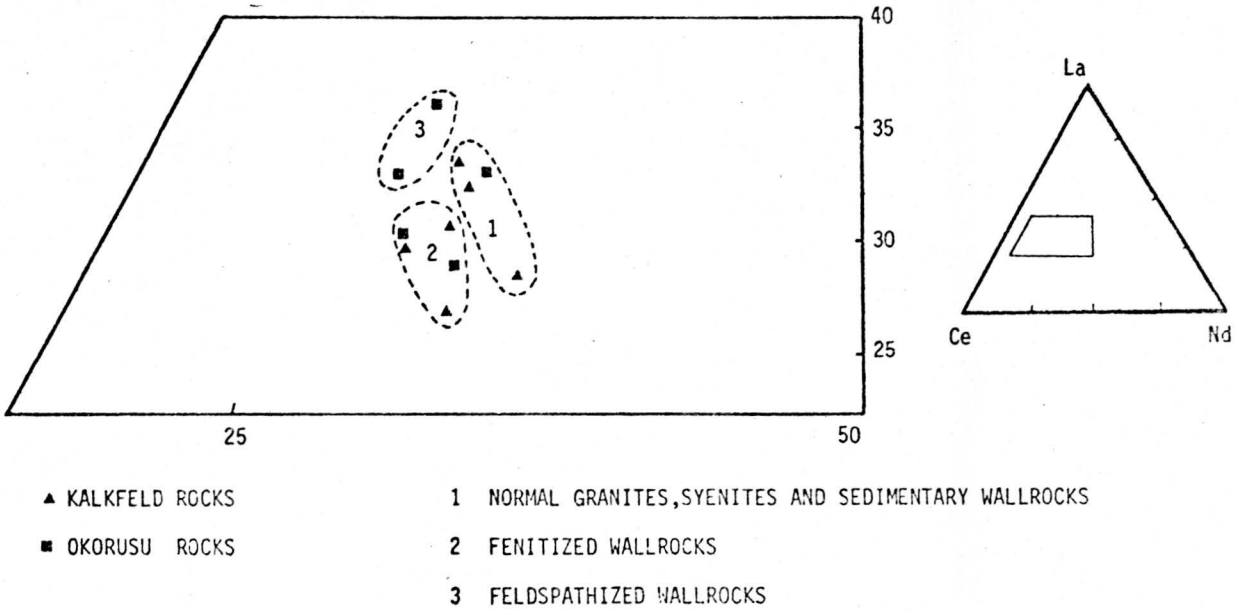


Fig. 47: Plot illustrating that the fenitized rocks are relatively enriched in Cerium whereas the feldspathized rocks are enriched in Lanthanum.

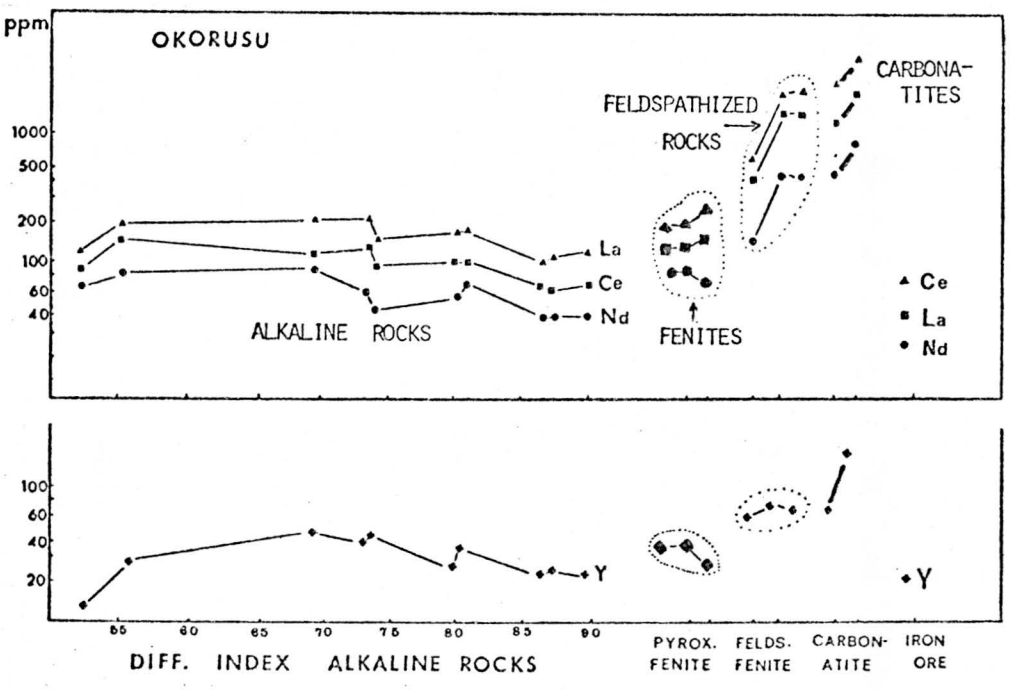


Fig. 48(a): Trace element content of alkaline, carbonatitic and metasomatic rocks from Okorusu.

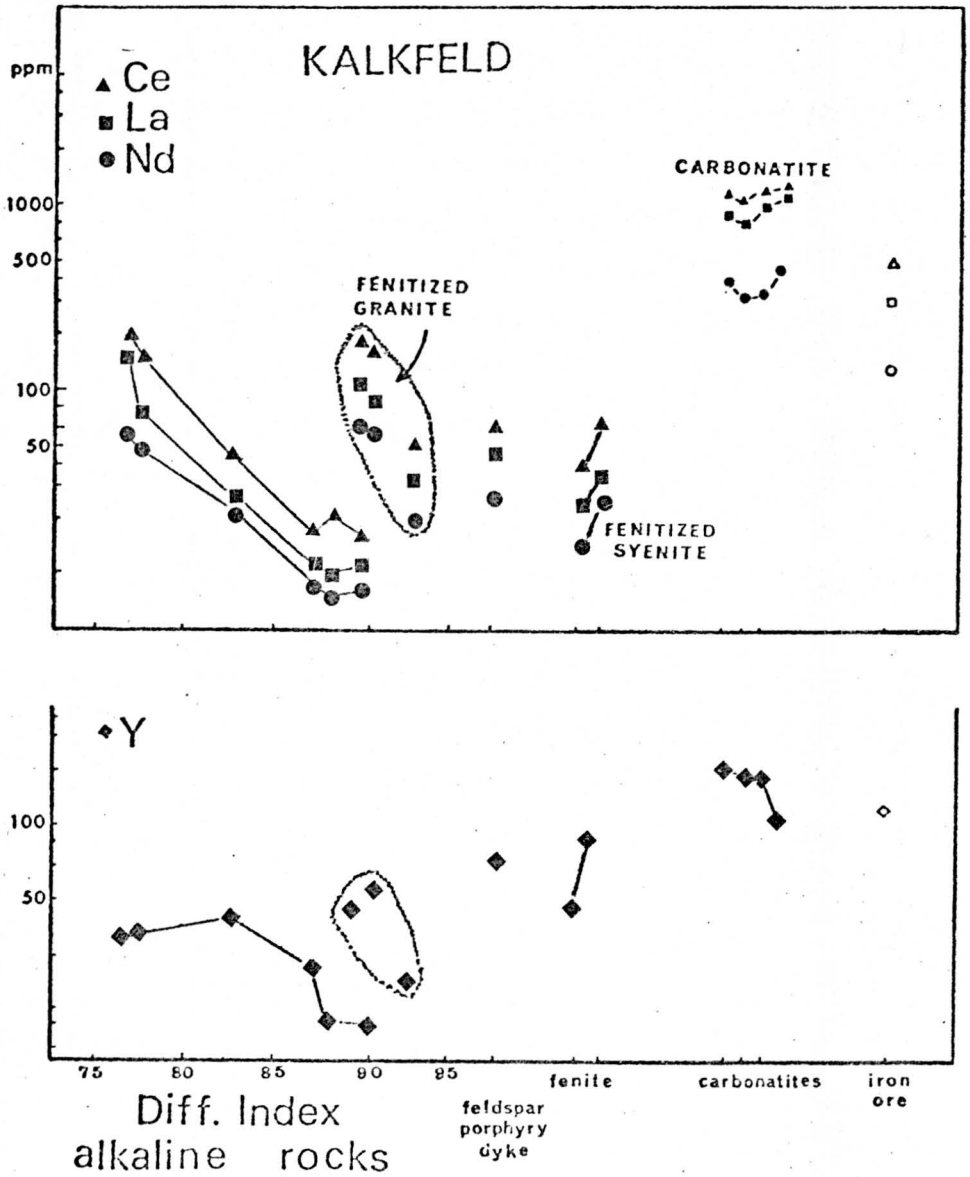


Fig. 48(b): Trace element content of alkaline, carbonatitic and metasomatic rocks from Okorusu.

that these metasomatic rocks were formed by the action of fluids escaping from a carbonatite magma.

4.5 FENITIZATION VERSUS FELDSPATHIZATION

The following gains and losses are typical of fenitization processes (McKie, 1966)

Si	large decrease
Na + Fe	large increase
Mg, K, Al, Ti, Mn, P	increase but may remain constant
Ca	tends to increase as calcite

These trends cover a broad spectrum of fenite types and are certainly misleading when individual occurrences are to be evaluated. The need for a simple and diagnostic classification scheme is thus obvious; especially since a number of recent studies indicate that fenitizing fluids may derive from different source magmas (Table 4). Woolley (1969) made a clear distinction between fenitization, nephelinization and feldspathization and suggested that the first two stages are associated with nephelinitic or phonolitic magmatism whereas feldspathization as well as sodium fenitization may be due to fluids derived from carbonatite magmas. However, the term fenitization is often used to describe sodium as well as potash metasomatism. This discussion attempts to delineate the differences between these two main trends.

More than 50 occurrences of fenitic rocks associated with alkaline/carbonatite complexes have been described in detail. Although most of these studies are of a petrographic nature some provide chemical data which were used in this study. Woolley (op.cit.) showed that the triangle Qz-Ne-Kp is particularly useful to indicate the changes in the felsic constituents during fenitization. He constructed such plots for a few localities and hinted that fenitic rocks can be broadly grouped into two types, i.e. those trending towards the $NaAlSi_2O_6$ corner and those that are more potassium-rich. He further suggested that a transition from sodium to potassium fenitization is connected with a change in the composition of the associated carbonatite magma. As the compositional changes during this type of metasomatism involve atomic substitution (Siemiatkowska and Martin, 1975) it is suggested that the plots proposed by Woolley should be based on molecular proportions rather than weight percentages.

Qx-Ne-Kp (mol. per cent) plots of 21 fenite occurrences are presented in Figs. 49, 50 and 51. These diagrams are used as a graphical representation only, as none of the data determined experimentally for this system and applicable to igneous rocks applies to fenites. It is apparent that the fenitic rocks from most localities plot on linear trends which are either inclined towards the Na-rich or towards the K-rich corner of the diagram, also, that no continuous change from Na to K fenitization exists for specific localities. However, fenitic rocks from a number of complexes can be interpreted as belonging to two separate trends, i.e. a Na as well as a K-enrichment trend (Fig. 51). As a first approximation it thus seems that fenitization processes can be distinguished

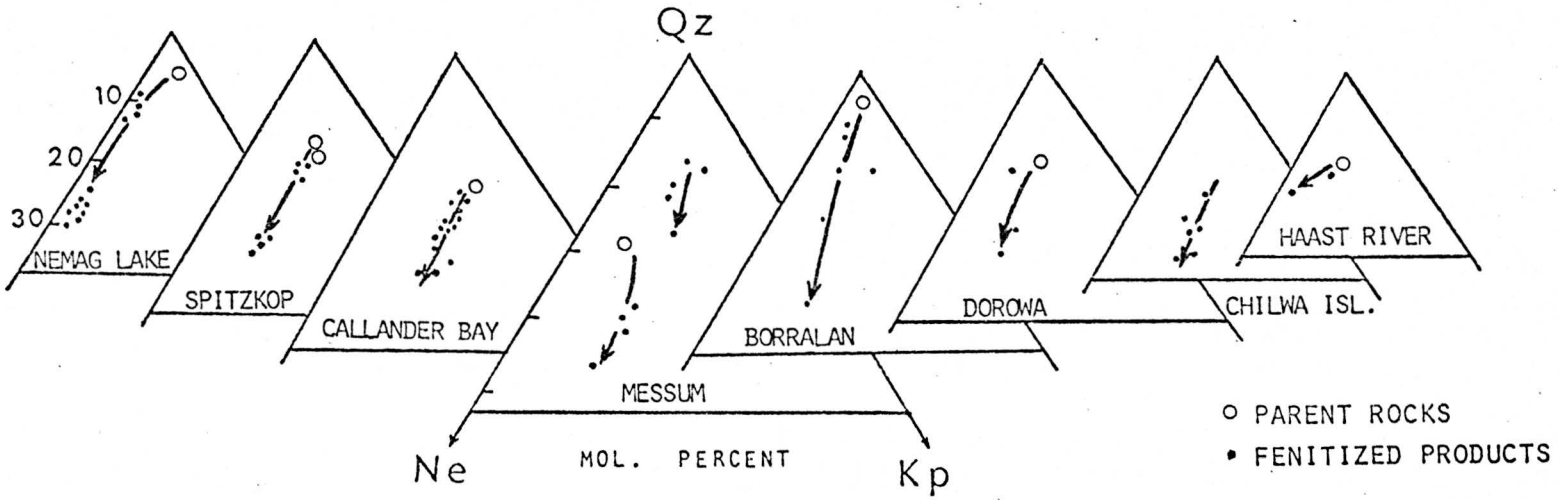


Fig. 49: Fenites showing Na-enrichment trends. These occurrences, except Chilwa Island, have all been ascribed to fluids derived from alkaline magmas.

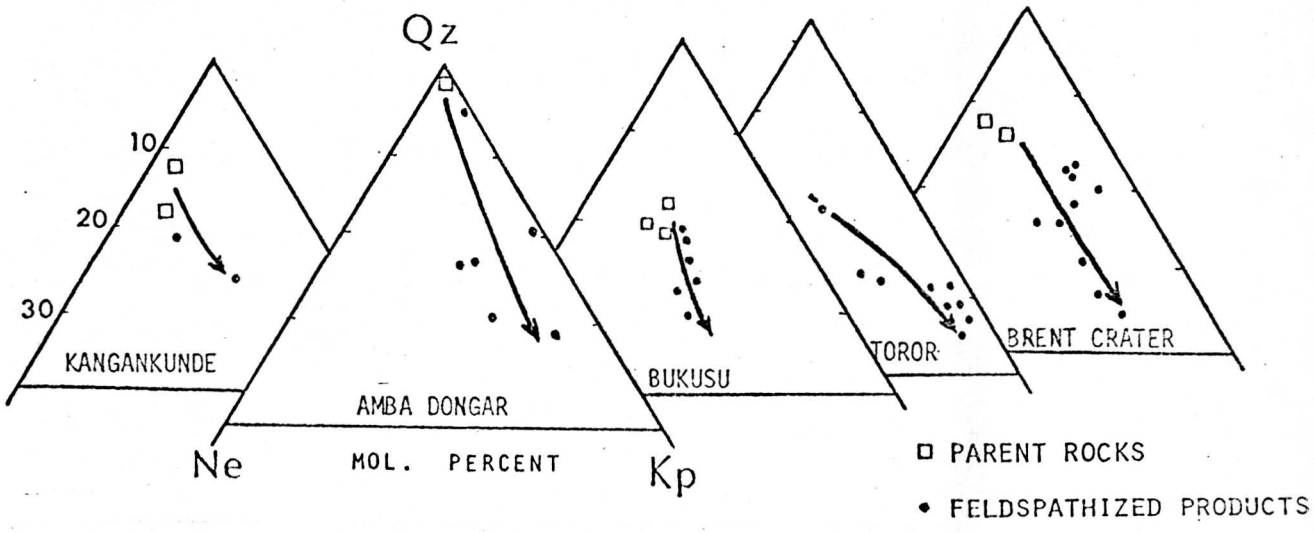


Fig. 50: K-enrichment trends of feldspathized rocks from carbonatite complexes. In these cases feldspathization has been ascribed to fluids derived from carbonatitic magmas.

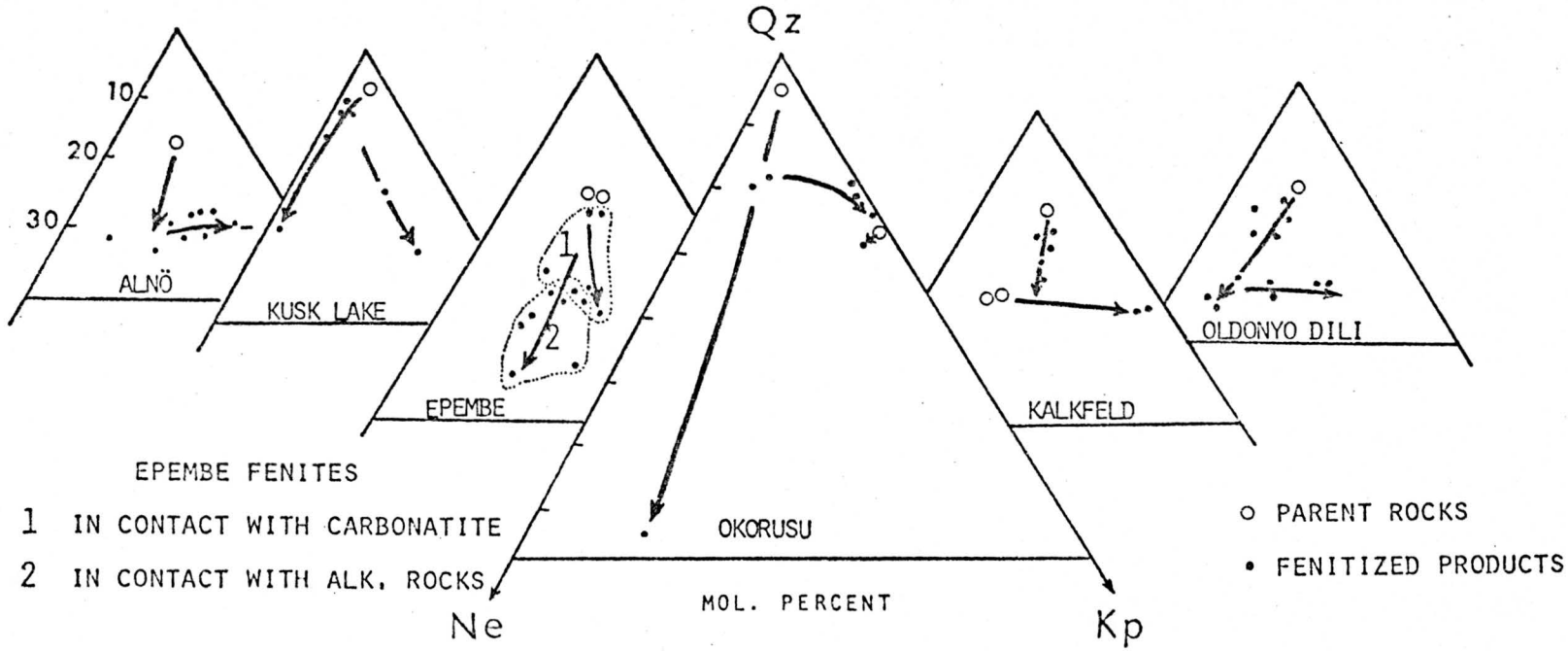


Fig. 51: Rocks showing a Na- as well as K-enrichment trend, most of these occurrences are associated with alkaline as well as carbonatitic rocks.

as of either a sodic or potassic nature and that some explanation should be sought for the occurrences showing a mixed or unclear trend. If two distinct types of fenitization occur in nature one would expect that two different fluids might be responsible for this phenomenon. Considering the fact that alkaline as well as carbonate magmas are usually present during the formation of an alkaline/carbonatite complex, an obvious explanation would be that the fluids derive from these two magma types. On the other hand, Ferguson, et al. (1975) suggest that the fenitization at Epembe resulted from the metasomatic action of fluids in equilibrium with both alkaline and carbonate magmas. A closer inspection of their data indicates that the fenitic rocks which are in contact with alkaline rocks are more Na-rich than those in contact with the carbonatite intrusion (Fig. 51). Could it be that the fluids derived from an alkaline magma are generally more Na-rich than those in equilibrium with a carbonatite magma? Ferguson, et al. (op.cit.) maintain that if the carbonatite magma originated through a process of liquid immiscibility from a siliceous magma the fluid phases in equilibrium with both magma types should have similar metasomatic effects. In their case the overall trend of the mafic and felsic fenites indicate a convergent composition of a syenitic nature.

Of those fenite occurrences with a Na-enrichment trend we find that only Callander Bay (Currie and Ferguson, 1971), Dorowa (Johnson, 1961) and Oldonjo Dili (McKie, 1966) have been ascribed to fluids derived from carbonatitic magmas. Looking at these instances in greater detail it becomes apparent that objections may be raised against the Na-fenite-carbonatite relationship. Although no carbonate rocks are present at Callander Bay, Currie and Ferguson (op.cit.) postulated a carbonatitic origin for the Na-rich metasomatic fluid because they believed that the K-rich nepheline syenite present could not have produced such Na-rich fluids as were operative at this complex. However, Woolley et al.(1972) subsequently suggested that the chemical changes during fenitization are not controlled by the composition of the source magma. As evidence they cited the development of reaction zones enriched in Na rather than K next to potassic syenite veins of the Borralan Complex. Thus no compelling reason exists why the Na-fenitization at Callander Bay could not be connected with the nepheline syenites of this complex.

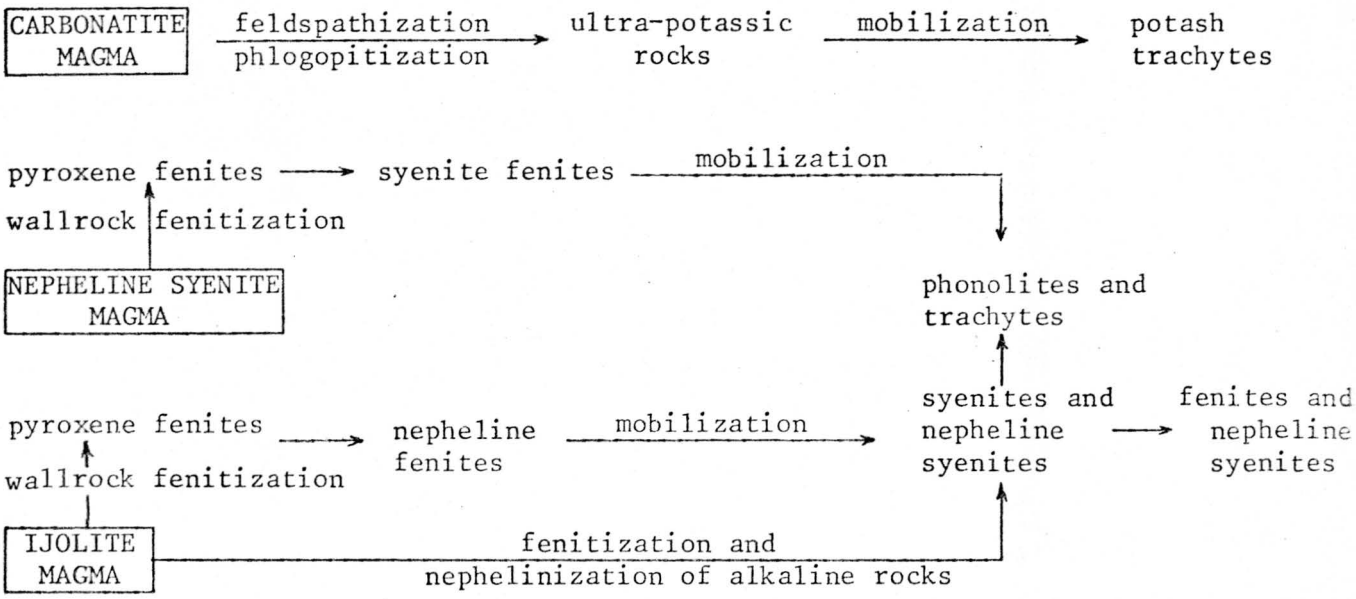
At Dorowa an oval ring of syenite fenite becomes increasingly syenitic towards a central area consisting of ijolitic and foyaitic rocks thought to be remobilized fenites (Johnson, op.cit.). The concentric arrangement of the fenite types around these ijolitic plugs suggests that these fenite aureoles formed

through fluids escaping from these bodies rather than from the carbonatite magma which formed only scattered and insignificant lenses and plugs. However, the development of a vermiculite-rich rock in contact with the carbonatite plug probably represents the metasomatic effects of a K-rich fluid derived from the carbonatite magma.

The well-studied fenite occurrences at Oldonyo Dili (McKie, op.cit.) have been ascribed to fluids derived from a carbonatite magma because at this complex carbonatite occurs almost to the exception of silicate rocks. The fact that the distribution of the carbonatite bodies bears no relationship to the concentric development of fenite zones, which increases in intensity of metasomatism inwards, and that some carbonatite bodies occur without alteration aureoles outside these fenite zones, again casts doubt on a Na-fenite-carbonatite relationship. If Oldonyo Dili is similar to the other Central-African carbonatite complexes, the existence of an ijolite-nepheline syenite magma in depth can not be excluded as a probable source for the fenitizing fluids. In fact, the concentric arrangement of the fenite zones are much more likely to have developed along an outward decreasing temperature gradient in a fluid column rising from a deepseated alkaline magma than from fluids associated with the small and irregularly distributed carbonatite dykes. Le Bas (1977, p.275) supports this idea.

If the arguments presented above are correct and these three occurrences of Na-metasomatism are not the result of a carbonatite fluid phase, then all the described fenite occurrences showing an enrichment in sodium could be due to Na-rich fluids derived from essentially K-rich alkaline magmas. A literature search reveals that nowhere up to date has potash metasomatism been ascribed to alkaline magmatism. Fig. 49 presents Qz-Ne-Kp diagrams for a number of fenite occurrences that all show marked potassium enrichment. These occurrences (except that of Brent Crater where no intrusive rocks are present) are in direct contact with carbonatitic rocks which are considered to have been the source of these K-rich fluids. It thus appears that K-metasomatism is exclusively associated with carbonatitic magmas whereas Na-metasomatism can generally be ascribed to fluids derived from alkaline magmas.

A scheme for fenite genesis, based on the one proposed by Woolley (1969) but modified according to the ideas presented here, is given below.

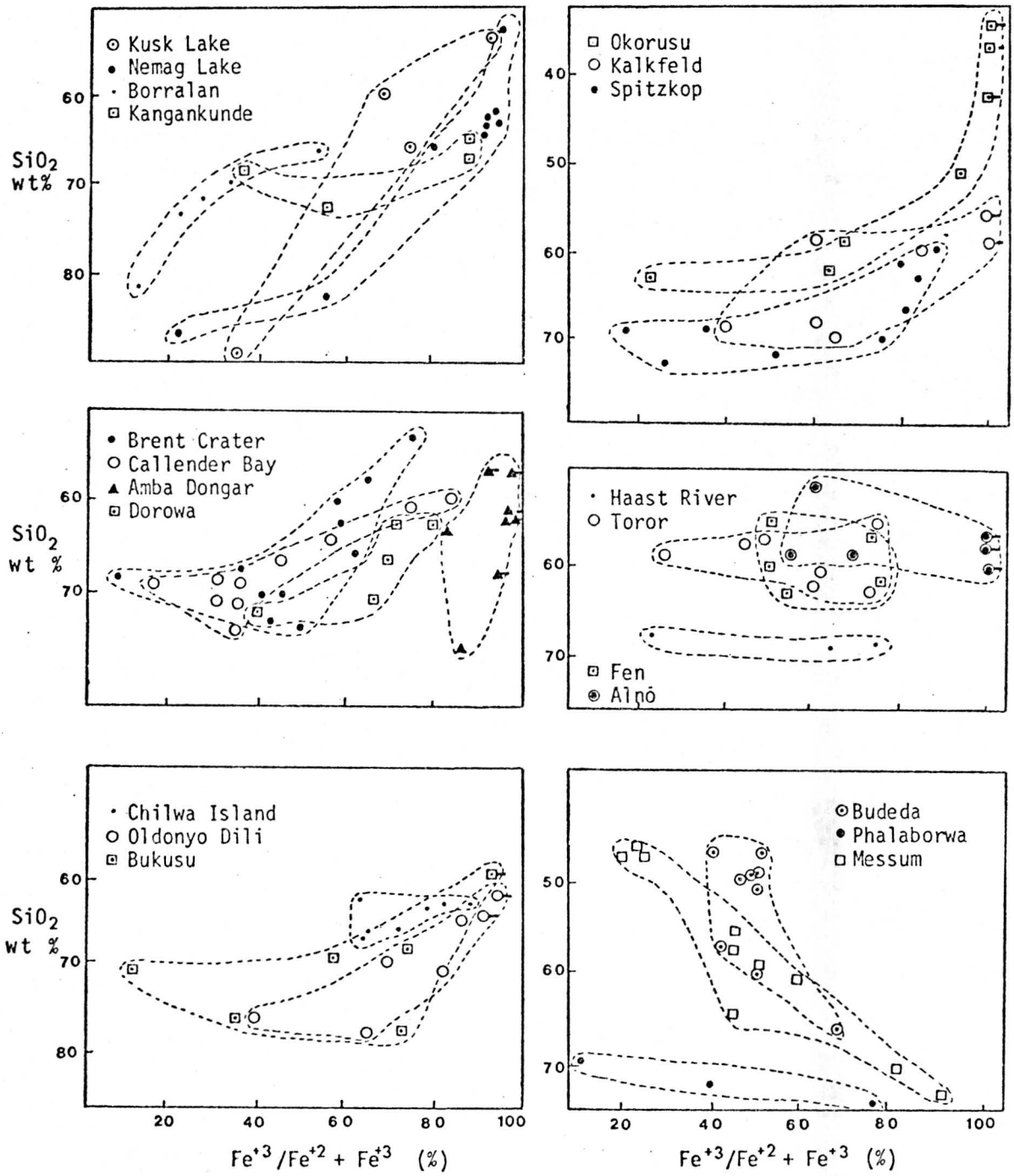


Fenitic rocks from occurrences such as Alnö, Kusk Lake, Epembe, Oldoyo Dili, etc., show a distribution on the Qz-Ne-Kp diagram which can be interpreted as representing two separate trends, i.e. a Na- and a K-enrichment trend. For instance, the Alnö plot (Fig. 51) may represent a major desilication process changing the country rocks and nepheline syenites to saturated syenitic fenites lying close to the Ab-Or join, followed by a potash enrichment process which moved the fenite compositions towards that of orthoclase. No trend is obvious for the Fen and Palabora fenites due to the limited number of analyses available from each complex. If, during the normal development of an alkaline/carbonatite complex the development of a Na-rich fluid is accompanied by a K-rich fluid it would be difficult to distinguish between the metasomatic effects of these fluids in rocks affected by both. A continuous change in the chemistry of the metasomatic processes i.e. from Na > K to K > Na would have to be inferred if the presence of a single fluid is proposed. Such deductions have been made by various workers e.g. Woolley, et al. (1972), Siemiatkowska and Martin (1974) and Rock (1976). That a fluid in equilibrium with a crystallizing magma would undergo slight changes in composition as the magma solidifies is not denied. However, it is doubted whether a single fluid phase in equilibrium with a specific magma type can produce such divergent metasomatic phenomena as are found at alkali/carbonatite complexes. It is believed more likely that two separate gaseous-fluid phases, one in equilibrium with a carbonatitic magma and the other with a silicate magma are responsible for the metasomatic phenomena associated with alkaline/carbonatite complexes.

4.5.1 Oxidation ratio

It has been shown by several authors that there is an increase in the oxidation ratio ($Fe_2O_3/Fe_2O_3 + FeO$) during fenitization (Von Eckermann, 1948; Verwoerd, 1966; McKie, 1966). The first author ascribes this phenomenon to the oxidizing action of CO_2 emanating from a carbonatite magma. If fluids derived from carbonatitic magmas are not the only fenitizing media in nature a re-evaluation of this generally accepted feature is necessary. Oxidation ratios of the fenitic rocks from the occurrences dealt with previously were calculated and plotted against their SiO_2 contents (Fig. 52). It is clear that the K- as well as the Na-rich fenites of most complexes show an increase in oxidation ratio with a decrease in SiO_2 content. However, a few complexes, notably Fen, Alnö, Toror, Messum, Budeda and Palabora do not conform to this trend; in fact, fenites from the last three complexes show a marked decrease in this ratio with fenitization, i.e. with decreasing SiO_2 content. The only characteristic which these anomalous fenite occurrences have in common and which distinguishes them from the rest is that they might not be true (first cycle) fenites but probably represent mobilized (melted) fenites. The original descriptions of these occurrences all mention this aspect very clearly. An increase in the oxidation ratio with increasing SiO_2 content, as shown by these complexes, is to be expected if we are dealing with magmatic conditions where an increase in P_{H_2O} normally accompanies fractional crystallization. Further studies to verify this relationship and its possible use in identifying mobilized fenites are obviously needed.

Fig. 52 also shows that K-fenitization results in much higher oxidation ratios than does Na-metasomatism. It can be seen that the feldspathic breccias, feldspar fenites and potash trachytes (mobilized fenites?) have very low FeO contents indicating the strongly oxidizing nature of the fluids derived from carbonatite magmas. Sodium fenitization also shows an increase in oxidation with desilication which means that fluids escaping from alkaline magmas are also of an oxidizing nature. The presence of $CO_3^{=}$ in fluids derived from a carbonatite magma will render the environment highly oxidizing. A fluid escaping from an alkaline magma will probably be less $CO_3^{=}$-rich but need not be less oxidizing as the dissociation constants of H_2O and $CO_3^{=}$ are very similar.



-FELDSPAR FENITES

Fig. 52: Variation of the oxidation ratio with wt% SiO_2 (extent of fenitization) of metasomatic rocks from alkaline-carbonatite complexes.

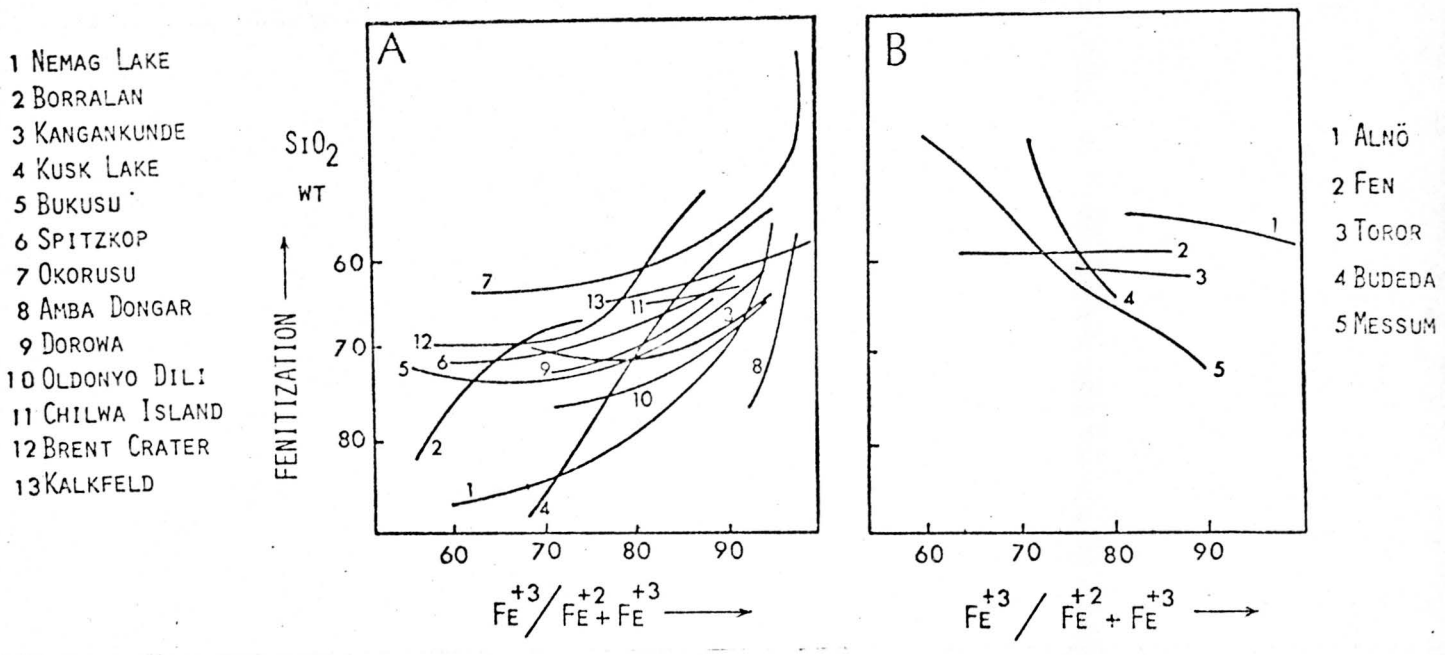


Fig. 53: (A) Oxidation trends of fenitized rocks (B) An increase in oxidation ratio coupled with an increase in SiO_2 might be the result of mobilization of fenitized rocks.

4.6 SUMMARY

An evaluation of the chemistry of 21 fenite occurrences indicates that desilication is the major process in their formation and that most occurrences can be classified as either of a sodic or potassic nature. Sodium fenitization (pyroxenitization) seems to be connected with fluids emanating from alkaline magmas whereas potassium metasomatism (feldspathization) occurs invariably in association with carbonatite intrusives. The oxidation ratio of both types of metasomatic rocks increases with progressive desilication. The feldspathic breccias and their mobilized products (potash trachytes) contain very little or no FeO. Rocks which probably represent mobilized first cycle fenites show a covariant relationship between their oxidation ratios and SiO_2 contents. This is considered to be a reflection of the conditions which prevailed during their crystallization from a melt.

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5 GEOCHEMISTRY OF THE DAMARALAND IGNEOUS PROVINCE

5.1 INTRODUCTION

The Damaraland alkaline province belongs to a major cycle of igneous activity which affected southern Africa during Cretaceous times. Extensive outpourings of basalt and intrusion of dolerite dykes occured after the close of Karoo sedimentation in northern South West Africa. The emplacement of alkaline ring complexes probably represent the later stages of this period of magmatism.

Insufficient petrochemical data and age determinations are available for the tholeiitic sheets and dykes which occur over large areas and in association with most of the ring complexes. The genetic relationship between these complexes and the so called Etendeka lavas will remain speculative until more data on the earlier tholeiitic magmatism become available. However, this study provides new information on the alkaline carbonatite complexes as a whole. The behaviour of major elements only was studied because trace element data are lacking for most of the sialic and basic complexes.

5.1.1 General petrology and age relationships

The extreme variation in the composition of rocks from the Damaraland alkaline province, viz. from tholeiitic to calc-alkaline as well as alkaline and carbonatitic associations represents one of the classic problems of igneous petrology. An important observation is that all the complexes, except those of a carbonatitic nature, contain tholeiitic and granitic (or rhyolitic) members as well as smaller quantities of alkaline rocks. The relative amounts of these rock types may vary between complexes but their presence remains significant as far as the

evolution of the complexes is concerned. Table 9 summarizes the rock types present at the individual complexes. (See also Chapter 1).

Table 9: Major rock types present at the Damaraland ring complexes (metasomatic rock types excluded)

Cape Cross	Messum	Okonjeje	Doros
basalt	basalt (tholeiitic)	gabbropicrite	gabbro
gabbro	olivine eucrite	gabbro	tillaïte
	microgabbro		
felsite		quartz syenite	
granophyre	porphyritic rhyolite	adamellite	
quartz porphyry	granophyre		
adamellite	microgranite	alkali gabbro	
		essexite	
nepheline syenite	nepheline syenite	pulaskite	
syenite	syenite porphyry		
essexite	nephelinite dykes		
tinguaite			

Brandberg	Erongo	Paresis	Etaneno
olivine basalt	olivine basalt	basalt, gabbro	sodalite syenite
quartz porphyry	rhyolite porphyry	feldspar rhyolite	nepheline syenite
	quartz porphyry	quartz-feldspar porphyry	
hornblende granite	granodiorite	comendite	
	granite	granophyre	
granophyre		syenite	
		bostonite	
		phonolite	
		tinguaite	
		microgranite	

Kalkfeld	Okorusu	Ondurakorume	Osongombo
nepheline syenite	monzonite	nepheline syenite	carbonatite
	ijolite	syenite	
syenite	nepheline syenite		
bostonite	syenite	carbonatite	
tinguaite			
	carbonatite	dolerite	
carbonatite			
	dolerite		
dolerite			

The few existing K-Ar determinations of Etendeka lavas indicate a maximum at 125 m.y. Ages of tholeiitic and gabbroic rocks associated with a few of the alkaline complexes range between 126 and 136 m.y. Gabbroic rocks from Okonjeje yielded an anomalous age of 164 m.y. (Siedner and Miller, 1968). Dolerite dykes dated by the above authors show three maxima, viz. at 125, 165 and 195 m.y. The main period of Etendeka and Damaraland volcanism coincides with that determined for the Serra Geral Formation and a number of alkaline complexes in Brazil (Amaral, et al., 1976; Hertz, 1977). The simultaneous and similar igneous activity of these regions as well as their correlation with the time proposed for the break-up of Gondwanaland suggest that the origin and geochemical evolution of the two magmatic provinces are related to the processes and conditions which prevailed during the initial rifting of the continents.

5.2 MAJOR ELEMENT GEOCHEMISTRY

5.2.1 Alkali-silica relationship

All available analyses of igneous rocks from the Damaraland province are plotted on an alkali-silica diagram (Fig. 54). No distinction has been made between intrusive, extrusive or hypabyssal rock types. The diagram is contoured according to the amounts of normative nepheline or quartz and according to the Thornton-Tuttle differentiation indices of the plotted rocks. Those that contain normative hypersthene with no qz or ne plot in a separate field in the lower part of the diagram.

The Damaraland analyses define an area (Fig. 54) similar to that shown by the rocks of the Gardar province, Greenland (Upton, 1974). A distinct feature of this plot (in which it differs from that of the Gardar province) is the paucity of points with differentiation indices between 40 and 60. This absence of intermediate compositions is also reflected in the histogram of SiO_2 values (Fig. 55).

On Fig. 54 the fields for tholeiitic and alkaline lavas of Hawaii (Macdonald and Katsura, 1964) are shown. It can be seen that the hy normative basaltic rocks cluster accross the dividing line so that rocks with alkalic as well as normal tholeiitic affinities occur at complexes such as Cape Cross, Messum, Paresis and Okonjeje. The Etendeka lavas also show alkaline as well as normal tholeiitic characteristics (Gevers, 1932). The felsic rocks from the abovementioned complexes plot as an isolated group and do not seem to represent differentiated

endproducts of basic magmas. As expected, rocks from the alkaline/carbonatite complexes define a field in the undersaturated (ne normative part of the diagram). These complexes are thus geochemically (and geographically) well separated from those which constitute the hy-normative cluster.

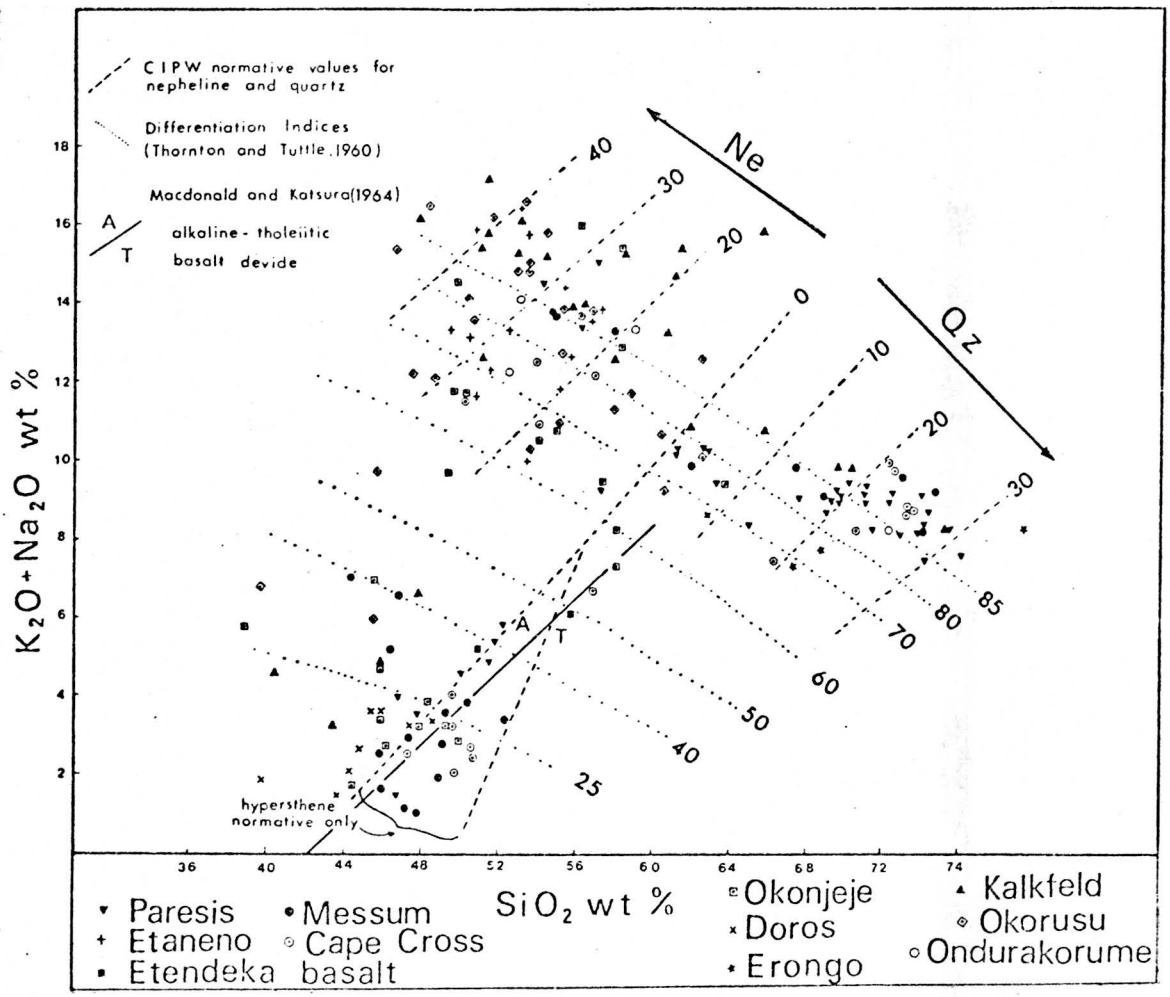

Fig. 54: Alkali-silica diagram for Damaraland igneous rocks, contoured for differentiation indices and normative nepheline or quartz.

Although the Damaraland rocks might belong to a single comagmatic igeous event it is clear that there exist a number of distinct rock series within the pro= vince. It seems that at least two parental magma types were present: one clearly of tholeiitic affinity and parental to the complexes in the western part of the province (Doros, Messum, Okonjeje and Cape Cross), the other nephelinitic in character and associated with the alkaline/carbonatitic complexes (Okorusu, Kalkfeld, Ondurakorume and Etaneno) in the northeastern part.

5.2.2 Bimodality of silica

The Damaraland alkaline province exhibits a frequency minimum for rocks of intermediate composition (Fig. 55). This feature has also been observed in other

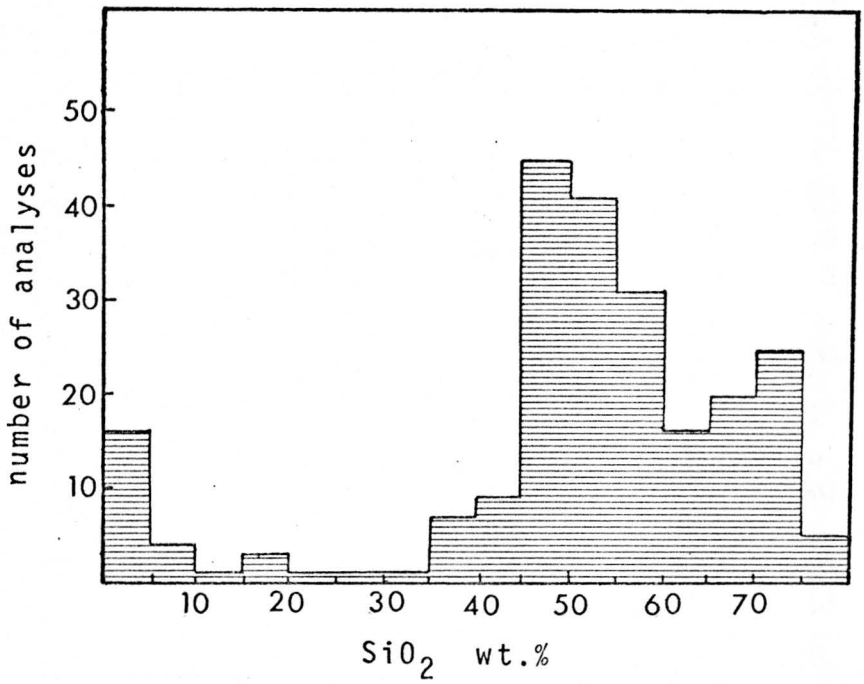

Fig. 55: Histogram of SiO_2 values of the available analyses of rocks from the Damaraland alkaline province. A frequency minimum occurs between 60 and 65% SiO_2.

alkaline provinces, e.g. the Gardar province South-West Greenland (Upton, 1974). Ferguson (1973) described a similar phenomenon for the Pilanesberg province without commenting on the cause. Chayes (1963) showed that for oceanic basalt-trachyte associations the frequency distributions of SiO_2, CaO, the Thornton-Tuttle differentiation index and to a lesser extent Na_2O, show a marked minimum value corresponding to rocks of intermediate composition. This so-called "Daly gap" has been explained by the difference in viscocity of felsic and mafic magmas (Le Maitre, 1968), the geometry of phase equilibria (Wyllie, 1963) or to a possible sampling bias. It has also been argued (Chayes, op.cit.) that the high ratio of felsic:mafic lavas in certain provinces can not be explained by simple fractionation crystallization of the observed volumes of basalt. This problem becomes significant only when the extreme rock types present have to be derived from a single parental magma. There is no reason why under certain

circumstances, different processes or episodes of magma generation can not be operative at different levels in the crust or mantle. Such processes are described in more detail in Chapter 7 (petrogenesis) where an explanation for the paucity in intermediate Si values of the Damaraland igneous rocks is offered.

5.2.3 The K_2O/Na_2O ratio

The Damaraland province can neither be termed potassic nor sodic. In the basic complexes sodium either predominates or equals the potassium content. (Fig. 56). On the other hand, much larger differences in the K_2O/Na_2O ratio exist among the rocks of the various alkaline/carbonatite complexes. The alkaline rocks of Kalkfeld and Ondurakorume are more K-rich than their counterparts from Okorusu. This is considered an important difference and probably reflects the crystallization of K-rich phases at the first two complexes. In contrast, the Okorusu magmas, especially the younger nephelinitic types, crystallized a more Na-rich alkali feldspar. The K-poor nature of the Okorusu melts is ascribed to the concentration of large amounts of potassium in a gaseous phase associated with a carbonatite magma which exsolved earlier. The extensive K-metasomatism at this complex supports the idea.

Van Zijl (1962) and Verwoerd (1967) suggested that the carbonatite complexes consolidated relatively close to the original land surface. Erosional and epeirogenic differences between the Okorusu and Kalkfeld localities are probably minimal. The difference in the K_2O content of the rocks exposed at these complexes would thus be difficult to explain in terms of the greater ionic mobility of potassium or by "transvaporization". These mechanism are frequently used by some authors, e.g. Szadeczky-Kardoss (1970) to explain the generally increased potassium content of high level alkaline intrusives.

5.2.4 Oxidation ratios

The composition of coexisting Fe-Ti oxide minerals has been used to predict the oxygen fugacity (f_{O_2}) and crystallization temperature of natural magmas (Buddington and Lindsley, 1964). To understand the factors which influence the Fe^{3+}/Fe^{2+} ratio of such liquids is therefore of prime importance. Carmichael and Nicholls (1967) showed that the Fe^{3+}/Fe^{2+} equilibrium in silicate melts is controlled by temperature and f_{O_2} as well as the alkali content of the liquid. These authors noted that an increase in $Na_2O + K_2O$ or an increase in the normative feldspathic

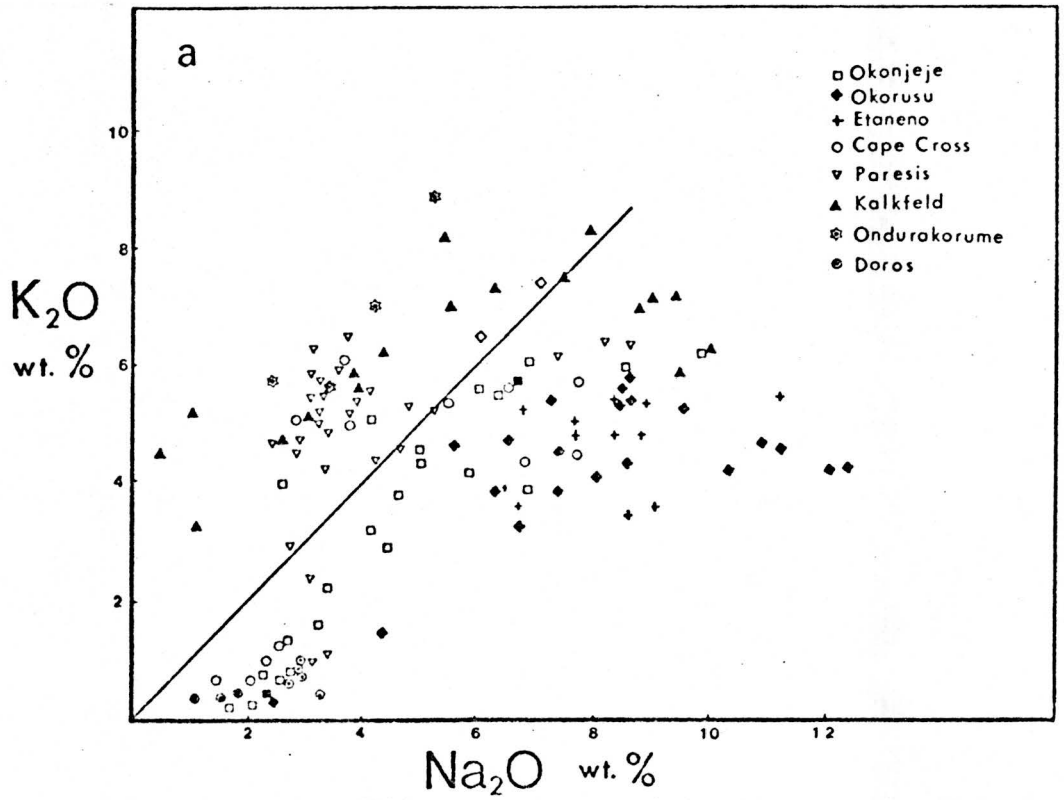

Fig. 56(a): K_2O-Na_2O diagram for Damaraland igneous rocks. The diagonal line indicates equal contents of K_2O and Na_2O.

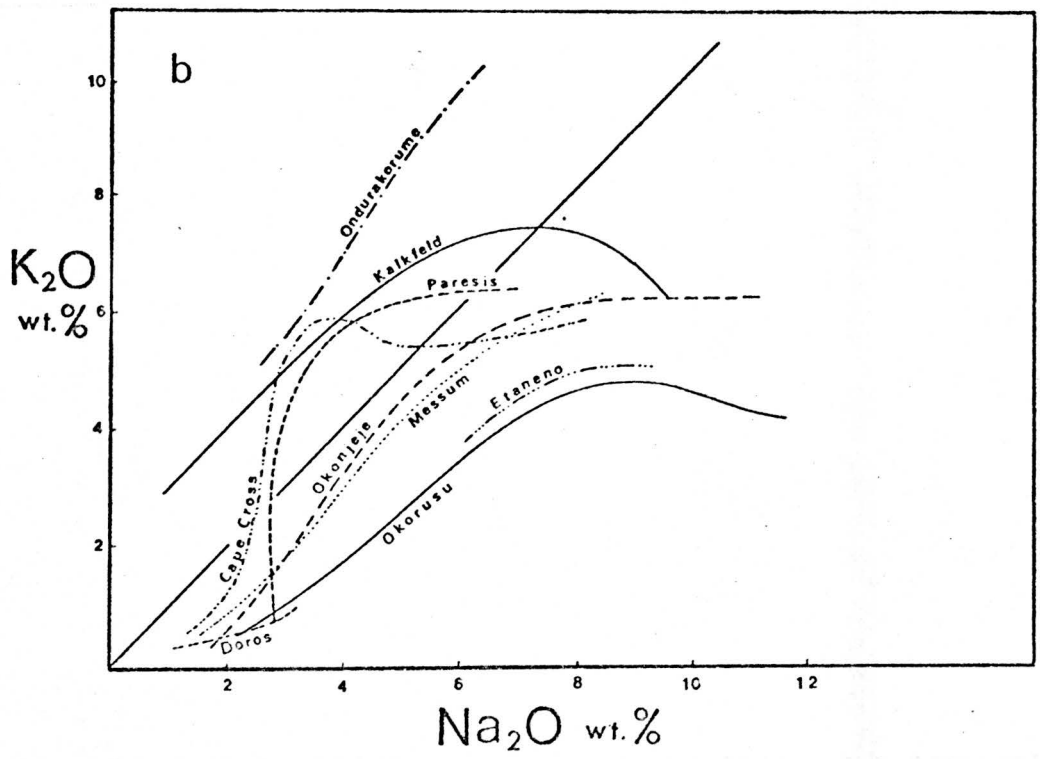

Fig. 56(b): Generalized trends for the individual complexes of the province as obtained from the distribution in (a).

or feldspathoidal components is coupled with an increase in the Fe^{3+}/Fe^{2+} ratio. Although this effect is enhanced by falling temperature it will be opposed if the f_{O_2} decreases during the last stages of crystallization - a trend which normally occurs in silicate liquids. They furthermore illustrated that the oxidation ratios of the average volcanic rock analyses compiled by Nockolds (1954) show a tendency to rise with increase in total alkali content. One may therefore conclude that residual liquids become more "oxidized" as fractionation proceeds and that the alkali content might play a significant role in this phenomenon.

A $Fe^{3+}/Fe^{3+} + Fe^{2+}$ against $Na_2O + K_2O$ plot (Fig. 57) of the available analyses of basaltic and alkaline rocks from the Damaraland province show no trend at all. However, when K_2O alone is plotted against the oxidation ratio of these rocks a significant trend does appear (Fig. 58). Similar plots for the individual complexes especially Okorusu, illustrate this relationship even better (Fig. 59). The scatter shown by these diagrams is probably due (at least in part) to subsequent oxidation of the Fe-bearing minerals. Metasomatism, especially during volatile-rich magmatism, might also influence the relationship between K_2O and the oxidation ratio. Therefore, only rocks described as truly magmatic were used in the above plots. In the case of Na_2O alone there is no sympathetic relationship with oxidation ratio (Fig. 57). The AFE (alkali: ferric iron effect) proposed by Carmichael and Nicholls (op.cit.) would therefore appear to be an oversimplification in view of the observation that it is the potassium content rather than the total alkalies, that influences the f_{O_2} of residual fluids. If the oxidation ratio of silicate liquids is influenced by its K-content and the composition of the oxide minerals reflects its Fe^{3+}/Fe^{2+} equilibrium, the iron-titanium-oxide geothermometer proposed by Buddington and Lindsley (op.cit.) will have to be calibrated, especially for K-rich igneous rocks. Why the presence of the potassium and not the sodium ion in a silicate liquid would have an effect on the oxidation ratio is difficult to envisage. It could be that the K_2O content is coupled to another parameter, such as a volatile phase which acted as an external buffer for the oxygen fugacity. The volcanic rocks from these complexes have some of the highest oxidation ratios among the rocks present. This could be due to external buffering of the oxygen fugacity of the volcanic melts by an associated water-rich phase which normally becomes important during the later stages of magmatism.

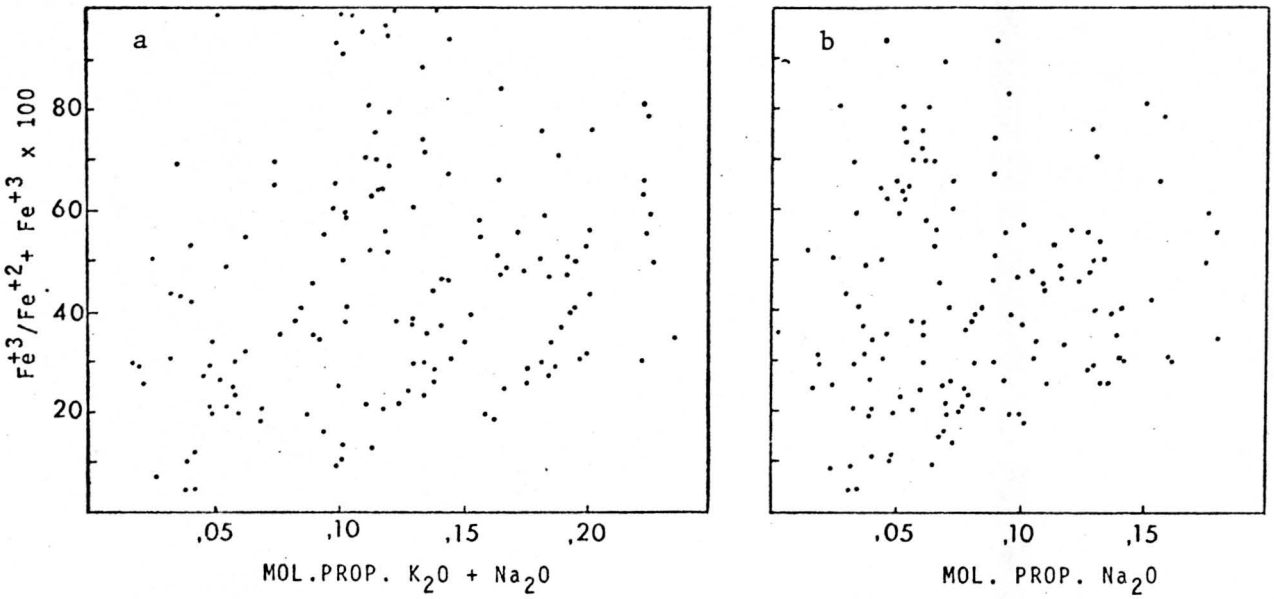

Fig. 57: Plot showing the absence of any relationship between the oxidation ratio and total alkalies(a) or Na_2O (b) of rocks from the Damara= land alkaline province.

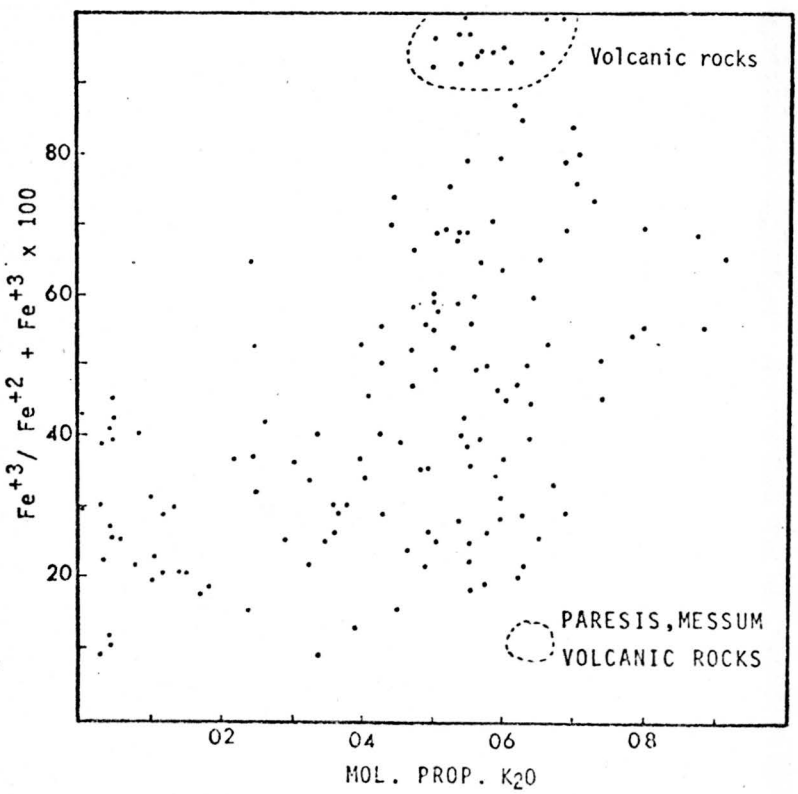

Fig. 58: Plot showing the relationship between the oxidation ration and the proportion K_2O of rocks from the Damaraland igneous province.

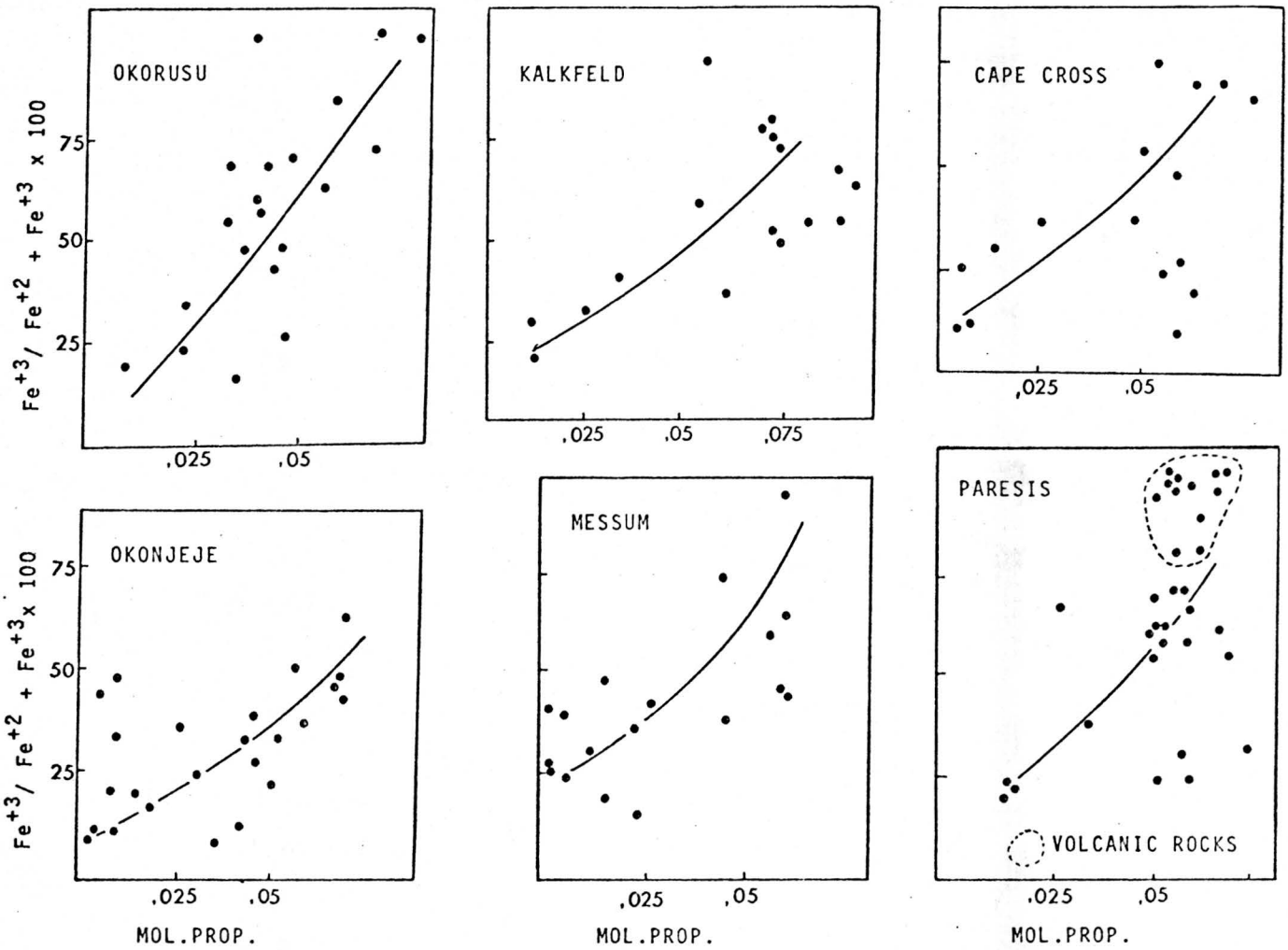

Fig. 59: Plots illustrating the relationship between the oxidation ratio and mol. prop. K_2O of rocks from the individual complexes of Damaraland.

5.2.5 AFM diagrams

An AFM diagram of all the available analyses of the Damaraland alkaline rocks shows a rather wide dispersal. This can be expected from a province exhibiting such extreme rock types (Fig. 60). However, a few separate trends can be identified. These trends are illustrated by similar diagrams of the individual complexes. The rocks of Cape Cross and Paresis plot on two well separated trends whereas those of Kalkfeld, Okorusu and Etaneno exhibit an alkali enrichment trend only. The Doros complex shows an iron-enrichment trend and no alkaline trend. The AFM diagrams of the Messum and Okonjeje complexes are strikingly similar and different from the rest in showing an apparently continuous trend from high Mg through constant Fe towards alkali enrichment. As in the previous section, it

appears that the tholeiitic rocks of Cape Cross, Paresis, Doros and probably Okonjeje and Messum (where metasomatism may be responsible for the rocks of intermediate composition) differentiated along a similar fractionation path from a dominantly tholeiitic parental magma. On the other hand, the ijolites, phonolites, syenites and nepheline syenites of the alkaline/carbonatite com= plexes must have differentiated from another (more alkaline) parental magma.

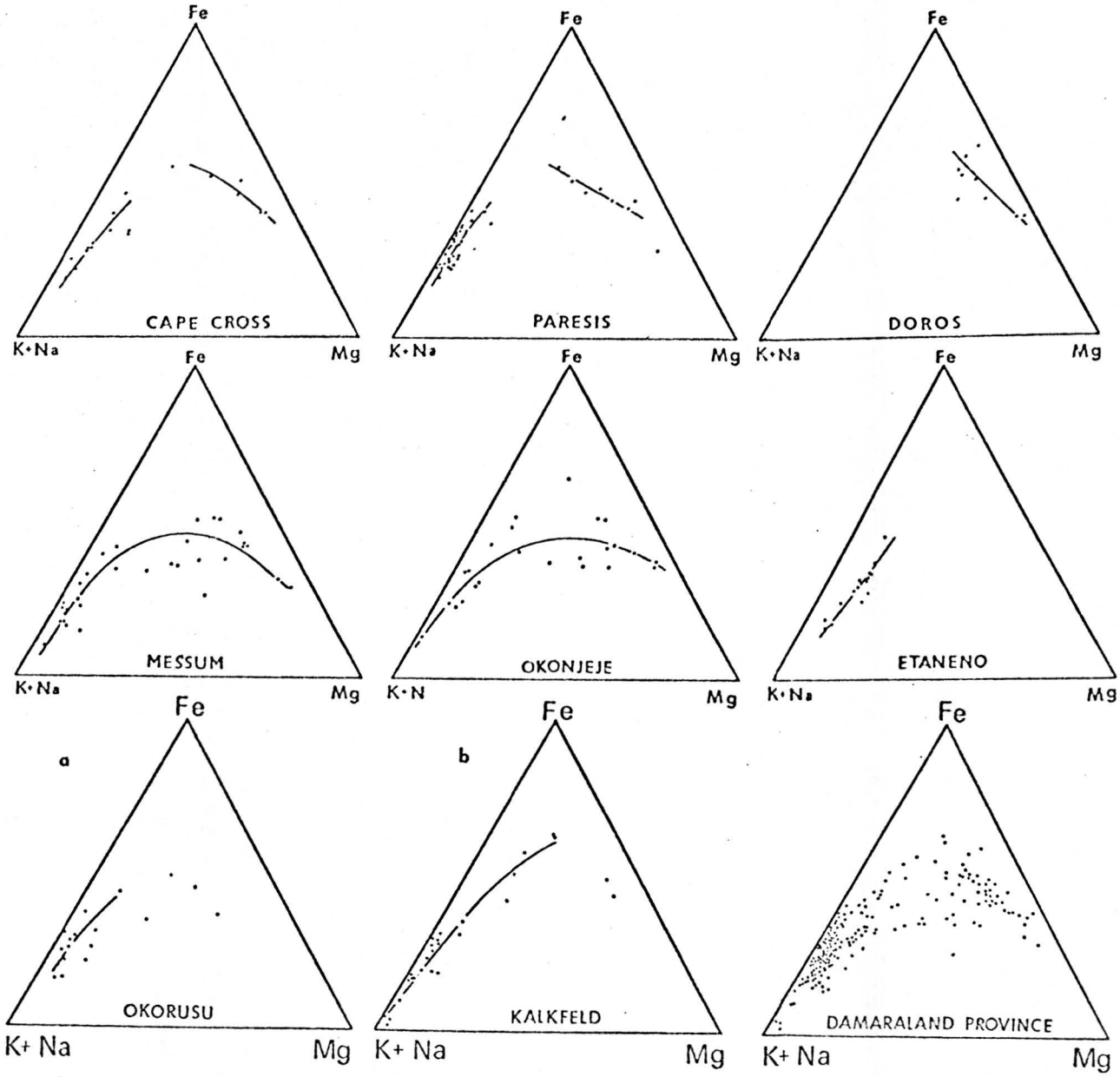

Fig. 60: AFM diagrams for the complexes of the Damaraland igneous province.

5.3 COMPARISON WITH OTHER ALKALINE PROVINCES

AFM diagrams were constructed and used to compare the major element variation in the rocks of the Damaraland igneous province with those of other alkaline provinces.

This province differs from most continental alkaline provinces in the presence of complexes of normal gabbroic composition (Doros), as well as in the associa= tion of large volumes of calc-alkaline granite with some of the basaltic com= plexes (Cape Cross, Messum). The latter feature is comparable with the excep= tional occurrence of biotite granite associated with the alkaline intrusives of the Oslo Province (Carmichael, et al., 1974) The tholeiitic, acid and alkaline magmatism which occurred in Damaraland finds a modern-day analogue in the volca= nic complexes of Jebel Al Abyad situated along the western coast of Saudi Arabia. This volcanic province has been described by Baker et al., (1973) as strongly al= kalic and primarily basic in composition. Older basaltic lavas (probably analo= gous to the Etendeka lavas) are abundant while phonolites, trachytes and agpaiitic trachytes also occur. Acid volcanics such as rhyolites and comendites are also present. The chemistry of these complexes shows a remarkable correspondence with those of the Damaraland complexes which are situated near the coast (Fig. 61). The reason for the similarity in chemistry is probably to be found in similar tectonic controls.

Figure 61 also shows that the Damaraland basic complexes, i.e. those near the coast, exhibit chemical features which are comparable to those of volcanic is= lands in the Atlantic ocean. This correspondence suggests that the magmatism which occurs during rifting on the continental edge evolves from the same magma reservoir that feeds the growing oceanic ridge. On the other hand, the alka= line/carbonatite complexes (further inland) exhibit a chemical trend which is analogous with that of other continental alkaline provinces, e.g. Pilanesberg, Gardar and Lüderitz.

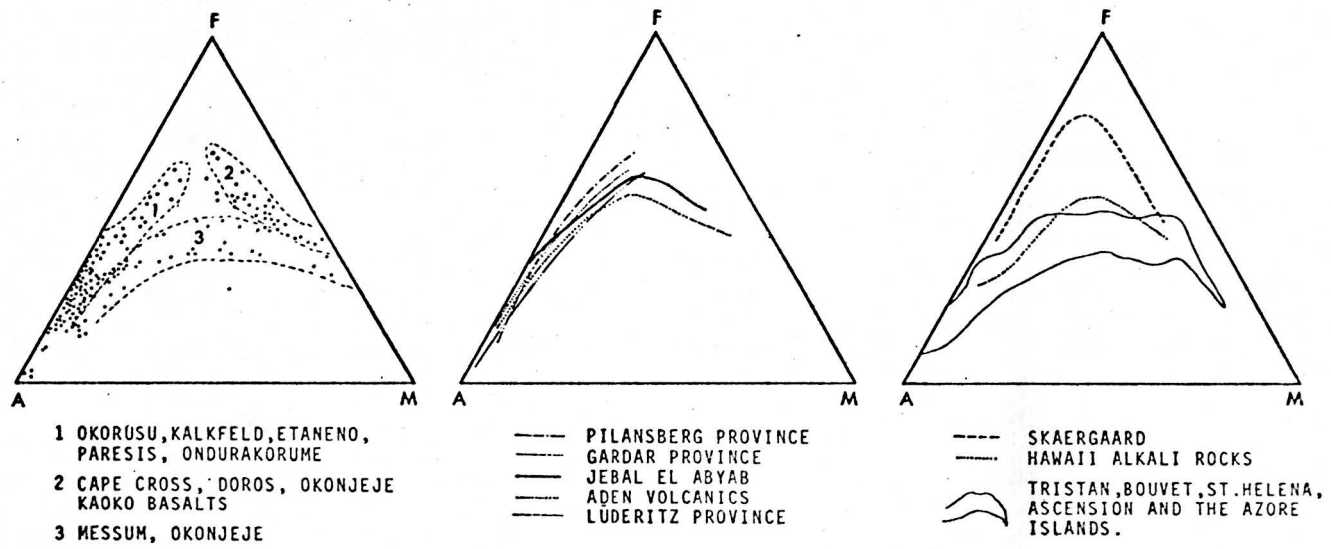

Fig. 61: Comparative AFM diagrams for the Damaraland and other alkaline igneous provinces.

CONTENTS

6 SOUTH WEST AFRICAN IGNEOUS LINEAMENTS AND THEIR RELATIONSHIP WITH GONDWANALAND BREAK-UP

6.1 INTRODUCTION

One of the most striking features of the Damaraland igneous province is that it extends along a well defined linear zone for a distance of 400 km inland, although it is not associated with any major faults. The occurrence of consanguineous (typically alkaline) magmatism along linear zones on the continents has been ascribed to various tectonic controls. The "plume" hypothesis as advocated by Morgan (1971) has been used by Duncan, et al. (1971), Burke and Wilson (1972), Wright (1973) Hertz (1977) to explain the linear distribution of such igneous activity. Bailey (1977) argued that the chemistry and volume relationships as well as the recurrence of magmatic activity along existing lineaments over a longe period of time contradict this hypothesis and proposed that continental uplift, arching and volatile influx exert the major control on alkaline magmatism. Marsh (1973) showed that some of the South West African and South American alkaline igneous provinces can be correlated with transform faults and suggested that these igneous lineaments represent transform directions which developed during the rifting of Gondwanaland.

The idea that transform faults are initiated along ancient fractures as outlined by Wilson (1965) has not received general acceptance except in a few cases (Snelgrove, 1970; Garson and Mitchell, 1970; Fail, et al., 1970; Fuller 1971). Recent support come from Garson and Krs (1976) who demonstrated that the rifting and associated magmatism of the Red Sea are controlled by existing structural weaknesses in the crust. The age and regional distribution of volcanoplutonic complexes along the southwest coast of Africa provide additional evidence. Recent discoveries in this area lead to the identification of new alkaline carbonatite provinces and to the extension of known igneous lineaments. These provinces

all extend from the coast in a northeasterly direction for a few hundred kilometres inland. Their development and tectonic setting have so far not been interpreted in terms of continental rift tectonics. In fact, their distribution and petrographic features differ markedly from those typical of the rift valley provinces. A systematic variation in the petrological nature of the complexes along these igneous lineaments seems to exist. Granitic and basaltic complexes occur near the continental margin and are followed by others of a more alkaline nature further inland. Kimberlitic intrusions are situated on the inland extensions of most of these lineaments.

6.2 ALKALINE MAGMATISM ALONG THE SOUTH ATLANTIC COAST OF AFRICA

Most of the 37 Angolan complexes are carbonatitic and/or syenitic in nature (Fig. 62). One granitic and four basic (diorite and diabase) complexes have

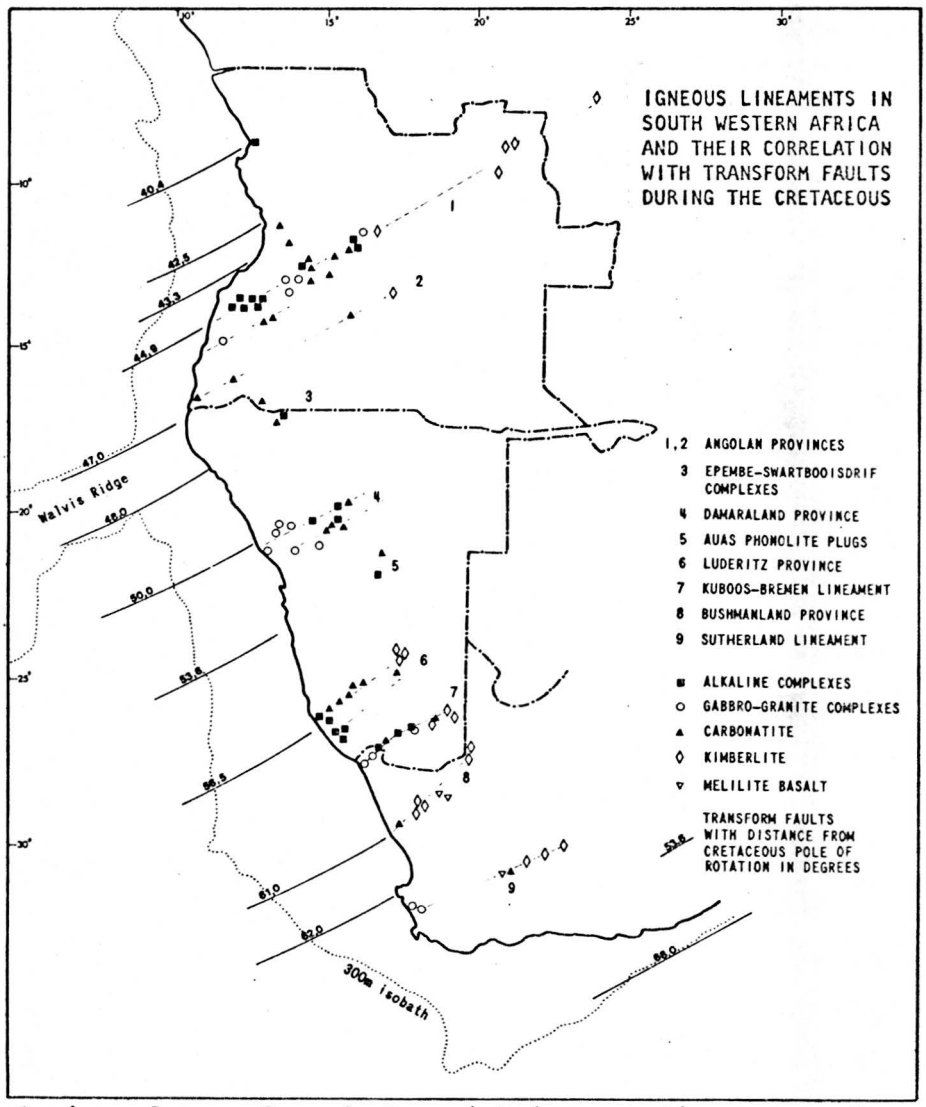

Fig. 62: Correlation of transform faults with igneous lineaments along the southwest coast of Africa. The transform faults have been extrapolated from the mid-ocean ridge along small circles around the Cretaceous pole of rotation according to Francheteau and Le Pichon (1972).

also been described by Lapido Loureiro (1973). There is little doubt that the location of these complexes is controlled by a set of NE-trending lineaments; at least three can be recognised. Rodriques (1974) suggested that an additio=nal NW-trending set is present, but it appears to be of lesser significance and can not be identified in similar provinces further to the south. Only one An=golan complex (Tchivira) has been dated, yielding an age of 112 m.y. Although Lapido Loureiro (op.cit.) considered the majority to be of similar age he sug=gested a younger age for some. Several important groups of diamond-bearing pipes occur on the extensions of these lineaments.

In contrast with the Angolan province the Damaraland province of northern South West Africa (Martin, et al., 1960) contains only a few alkaline intrusions. Age determinations (120-135 m.y.) indicate that the great volcanoplutonic com=plexes of Messum, Paresis, Brandberg and Erongo undoubtedly belong to the same province (Siedner and Miller, 1968). The emplacement of these complexes was accompanied or followed soon after by the outflow of the basaltic Etendeka la=vas (115 m.y.) along the margin of the continent. It has been suggested (Prins, 1976) that in some of the complexes granite and basalt are closely asso=ciated and that the tholeiitic flows surrounding or partially overlying the gra=nite plutons (Cape Cross, Brandberg and Erongo) are genetically related to the plutons and not to the regional plateau basalts as previously thought. The Okonjeje complex has been dated at 164 m.y. (Siedner and Miller, 1968), an aber=rant age which exceeds that of the other complexes as well as the proposed age for the initial breakup of Gondwanaland by nearly 30 m.y.

Further south nepheline syenite complexes at Granitberg and Pomona (Marsh, 1976) and a number of recently discovered carbonatite complexes (Dicker Willem, Teufel=kuppe, Keishöhe and Kaukausib) constitute the Lüderitz province. Age determi=nation (K/Ar) on biotite from a nepheline syenite of Granitberg yielded an age of 130± 2 m.y. (Marsh, 1975). The Klinghardt phonolites which yielded ages of 37± 1 m.y. and 35,7 m.y. (Kröner, 1973) and the Gross Brukkaros volcanic vent are situated in the same area and probably represent a recurrence of igneous activity along the same zone of crustal weakness in later times. The cluster of kimberlitic pipes near Gibeon belongs here as well.

A number of granitic, alkaline and carbonatite complexes are situated on two slightly divergent lineaments 300 km south of Lüderitz near the Orange river mouth. This so-called Kuboos-Bremen igneous province differs from the others

along the coast in that several of its members have been dated at 506-550 m.y. (Kröner, 1973). In fact, the Bremen complex has an earlier intrusive unit dated at 920 m.y. which indicates that magmatism was repeated along the same conduit after an interval of 400 m.y. A swarm of carbonatitc lamprophyres are found deeper inland on the same lineament and is undoubtedly of a younger age (Schreuder, 1975).

The existence of igneous lineaments further south is less certain. However, a carbonatite complex recently discovered at Zandkopsdrift (Verwoerd, 1978) together with the Bushmanland olivine melilitite and kimberlite swarms to the northeast (Cornelissen and Verwoerd, 1975) as well as a few kimberlite pipes on the South West African border might constitute an igneous lineament. These melilitite and kimberlitic rocks have been dated at 68-72 m.y. (Davis, et al. 1976).

The presence of another igneous lineament running through the Saltpetre Kop car= bonatite and nearby melilitites towards a few non-diamondiferous kimberlite pipes near Fraserburg and Victoria West is suggested. The gabbro and diorite plugs near Yzerfontein and Malmesbury, tentatively dated at 586 m.y. (A.E. Schoch, personal communication) are situated exactly in line with the above. This could be another instance of igneous activity over a long time interval along a deep-seated lineament, parallel to those in Angola and South West Africa.

It is clear that the majority of igneous complexes near the Atlantic coast of southern Africa are considered to be of an age which corresponds to that proposed for the early opening of the South Atlantic. This suggests that the origin of these rocks in contrast with that of the rocks from the rift valley provinces, is connected with the tectonic conditions associated with the separation of the continents. Magmatism in some of these lineaments was not restricted to Meso= zoic times but started in the Precambrian and recurred during the Oligocene. This indicates that the northeasterly trend of these lineaments is not a Mesozoic feature but that it reflects a deepseated structural grain of the continent and that the lineaments were localised by primary disjunctive structures in the crust. An orthogonal NE-SW and NW-SE fracture system has previously been suggested for the African continent (Furon, 1963; Rodriques, 1972). The existence of similar systems of "deep-seated tectonic zones" have been recognized in many parts of the world (Stovickova, 1973; Garson and Krs, 1976).

6.2.1 Structural controls

The controls over intraplate magmatism are not as easily explained by modern plate tectonic mechanisms as is the case with plate margin magmatism. Marsh (1973) proposed that some of the above-mentioned igneous lineaments, viz. those of the Angolan, Damaraland and Lüderitz provinces as well as similar provinces in South America are transform directions which are the continental extensions of fracture zones that offset the mid-Atlantic ridge. This pro= posal was based on the fact that these lineaments lie on the same small circles (centered on the Cretaceous pole of rotation) as the transform faults listed by Francheteau and Le Pichon (1972).

Moore (1976) distinguished four major phases of alkaline volcanism in southern Africa and correlated them with major marine regressions. These regressions he ascribed to marginal upwarping of the sub-continent which also triggered the alkaline magmatism. Scrutton and Dingle (1974) also accepted the position of transform faults along the southwest coast of Africa as proposed by Francheteau and Le Pichon (1972) and suggested the presence of one more such fault on the evidence of off-shore basins of deposition. These transform faults and the position of the igneous provinces along the southwest coast of Africa are indi= cated in Fig. 62. This figure shows that not only the three lineaments recog= nised by Marsh fit the pattern but the others as well. Especially noteworthy is the fact that their spacing on land is nearly the same as the spacing of the transform faults projected from the mid Atlantic ridge. Furthermore, none of the known transform faults coincide with the position of the Precambrian Kuboos-Bremen province. This is exactly what would be expected if the structural trend was in existence since the Precambrian but was not reactivated in this particular area during continental break-up.

Two fracture zones, viz. at 48^{o} and at $53{,}6^{o}$ do not coincide with known igneous lineaments on the continent. Nevertheless, alkaline intrusions which apparently do not belong to any known lineament are situated opposite these fracture zones. The post-Karoo Auas phonolite plugs (Martin, et al., 1960) and a newly discovered (Precambrian?) carbonatite at Okahandja (Gunthorpe, personal communication) may perhaps form part of igneous provinces hitherto unidentified due to vast sand cover to the southwest and northeast.

The position of a fracture zone at the southern boundary of the Walvis Ridge (48^{o} cicle) as postulated by Le Pichon and Hayes, (1971) coincides with the

Epembe and Swartbooisdrif alkaline carbonatite complexes which are of Precambrian age (Simpson and Otto, 1960). If these complexes and the Kunene anorthosite mass in Southern Angola were emplaced along a deep-seated fracture it might well be that the development of the Walvis Ridge itself was also controlled by this pre-existing crustal weak zone. Unfortunately any evidence of an igneous lineament in this area is again obliterated by the Kalahari sand cover. It should be emphasized that the transform faults in the ocean basins have nowhere been found to extend all the way to the continental margin and on to land. This seems to be the hypothesis favoured by Marsh (1973) and Girdler (1968) in the South Atlantic and Red Sea areas respectively. However, as described by Garson and Krs (1976) for the Red Sea area, the Angolan and South West African igneous lineaments probably respresent pre-existing lines of crustal weakness that controlled the location of transform faults initiated during rift movement.

The alkaline/carbonatitic nature of the continental magmatism that coincide with this event points to the deepseated nature of the tectonic and magma generating processes that were operative below the continents during their separation. The idea is not that tensional stresses (Marsh, op.cit.) which originate at transform faults are transmitted into the asthenosphere underlying the continent. Rather, it could be that plate movement is accompanied by a redistribution of intraplate stress conditions and that these become focussed along existing deep-seated fractures. Linear regimes of partial melting would thus develop in the weak zones in the lower crust located at the ends of the transform arcs. The growth of the transform faults would have been accompanied by small-scale re-adjustments in the adjacent continental weak zones. Such readjustments need not necessarily have suface expressions in the form of faulting but would allow the tapping of the linear melting regime. The ultimate emplacement of the magmas would be controlled by the structural grain of the upper lithosphere.

6.2.2 Petrological variations

The systematic change from gabbroic-granitic to alkaline-carbonatitic complexes inland (Damaraland province) and the alternation of alkaline and calcalkaline complexes followed by kimberlite (Angola) still have to be explained.

Taken together the groups of kimberlite pipes on the NE-trending lineaments define a north-south line which does not follow the present-day coastline but parallels the continental margin before it swings eastward in the south. The alkaline and carbonatite complexes occur at similar distances from the continental

margin independent of the present day coastline. The same relationship is illustrated by the basic and granitic complexes. It is suggested that a series of up- and downwarps developed parallel to the rifted coastline during the dis= ruption of the Gondwana super-continent. The upwarps localised the emplacement of alkaline and carbonatite complexes whereas the downwarp axes corresponded with the positions of acid and basic intrusions. The kimberlite boundary is considered to indicate the beginning of a major downwarp (Fig. 63). A warp

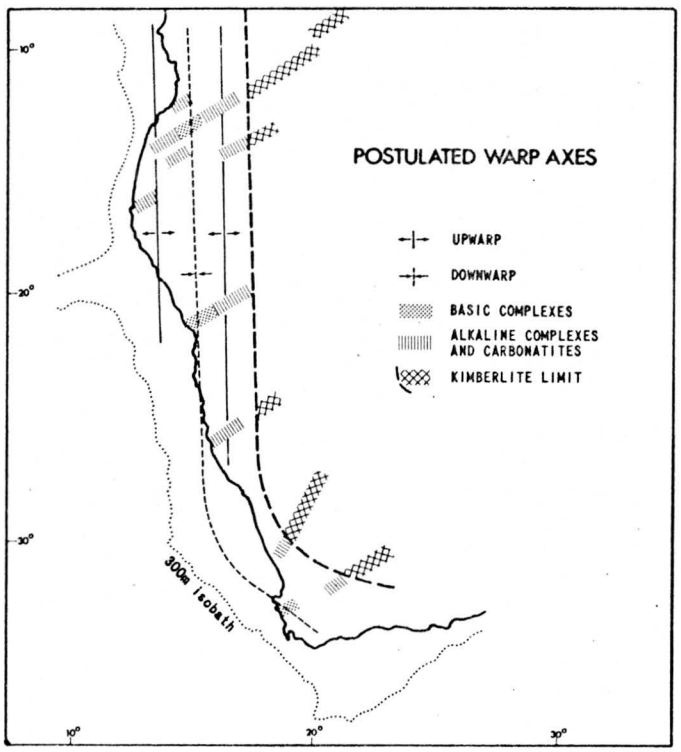

Fig. 63: Postulated Mesozoic warp axes along the southwestern coast of Africa. Alkaline and carbonatite complexes occur on the upwarps whereas the basic/granitic complexes are located in the downwarped areas.

axis parallel to the South West African coastline has previously been suggested by Martin (1973) as well as Moore (1976). The proposal of Burek (1973) that the North American continent underwent a series of undulations during its break= away from Eurasia provides an analogy to the upwarps proposed here. As in the case of North America the upwarps appear to increase in wavelength away from the continental margin.

The upwelling wedge of magma forming the new oceanic floor must have caused an increase in the geothermal gradient in the adjacent continental crust. The emplacement of large volumes of basaltic magma probably triggered the partial

melting of the already heated crustal material. This resulted in the in= trusion of basaltic and granitic magma along the same channelways as illustrated by the Damaraland complexes. It has been shown by Prins (1976) that the basic rocks from these basaltic/granitic complexes along the coast have chemical cha= racteristics analogous to those of the islands of the Atlantic Ocean. Outside these regions of abnormal heatflow and coupled with an increase in crustal thick= ness, partial melting probably commenced at a greater depth. This resulted in magmas richer in alkalies as indicated by the more alkaline nature of the com= plexes further from the continental margin. Where the linear zones of partial melting which developed along existing deepseated fractures coincided with the upwarps into which volatiles had been fluxed, carbonatitic magmatism occurred (Fig. 64). The few ages available for kimberlitic rocks in this area (Davis, et al., 1976) indicate a younger age(69-90 m.y.) than that proposed for the initial

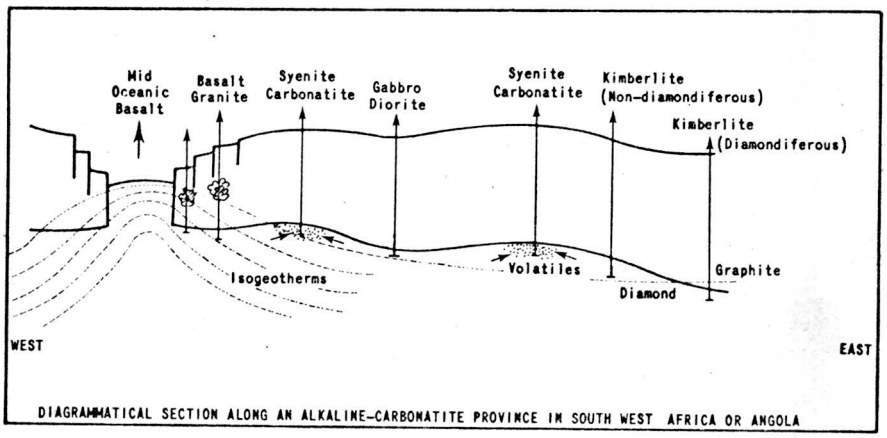

Fig. 64: Diagrammatical section illustrating the petrological variation of central complexes along an alkaline/carbonatite province in South West Africa of Angola.

opening of the Atlantic. However, their situation suggests that pre-existing crustal weak zones provided not only the focal points for alkaline magmatism during the initial breakup of Gondwanaland but also the passageways for kimber= litic intrusions in later times.

If this hypothesis is correct, one would expect to find similar evidence in other parts of the world.

6.3 EVIDENCE FROM THE ATLANTIC COAST OF SOUTH AMERICA

Alkaline and carbonatite igneous activity in Brazil occurred during two major intervals, viz. 122-135 and 51-82 m.y. ago (Amaral, et al., 1967; Hertz, 1977). Complexes belonging to the earlier period are situated along a lineament which Marsh (1973) correlated with a transform direction that coincides with a 44^{o} small circle centered at the Cretaceous pole of rotation between Africa and South America. The younger complexes also have a linear distribution and can be linked with another transform direction, this time coinciding with a 90^{o} small circle centred at the present pole of rotation. These complexes contain rock types which are not only analagous with those found in the Damaraland and Angolan provinces but also show the same petrological variation with distance from the continental margin. The complexes near the coast (Casimiro de Abreu, Cabo Frio, Montão de Trigo, São Sebastião) are of alkaline-gabbroic nature where= as alkaline and carbonatitic complexes occur further inland, e.g. Poços de Caldas, Araxà, Itapirapua and Jacupiranga. Kimberlite diatremes have recently been dis= covered in the vicinity of the major alkaline/carbonatite occurrences (Svisero, 1977) and are believed to be of post-Cretaceous age, as in south western Africa. (Fig. 65).

De Almeida (1972) described the post-Jurassic tectonic history of the eastern part of the South American platform in terms of the reactivation of Precambrian faults and the formation of sedimentary basins between uplifted arches along the continental margin. Further inland the Paranà and Chaco synclines are separated by the Central Paraguayan anticline in which several centres of alkaline magma= tism developed between the end of the Jurassic and early Cretaceous (Conte and Hasui, 1971). In broad outline these tectonic features may represent a set of undulations similar to those proposed for the southwest coast of Africa (Fig. 63). Alkaline and carbonatite magmatism is again confined to the upwarped areas where= as basaltic and granitic magmatism seem to predominate in the downwarped regions.

The relatively isolated group of alkaline/carbonatite complexes in northern Minas Gerais, viz. Araxà, Tapira, Catalão, etc., belong to the younger group of intru= sions and is situated directly opposite the Vittoria-Trinidade rise. Undated granitic intrusions occur near the coast in association with basaltic outpourings and are also in line with this rise. These intrusions lie more or less on the small circle centered at 44.4^{o} around the Cretaceous pole of rotation which Francheteau and Le Pichon (1972) suggested coincides with a transform fault.

It may thus be that carbonatitic activity occurred inland on an upwarp axis and in line with a transform fault. Upper crustal structures probably deter= mined the local NW-SE alignment of individual complexes.

A number of other alkaline provinces occur along the east coast of South America, e.g. in Rio Grande do Sul and in Uruguay. Figure 65 indicates that they can all be correlated with specific fracture zones as proposed by Francheteau and Le Pichon (1972).

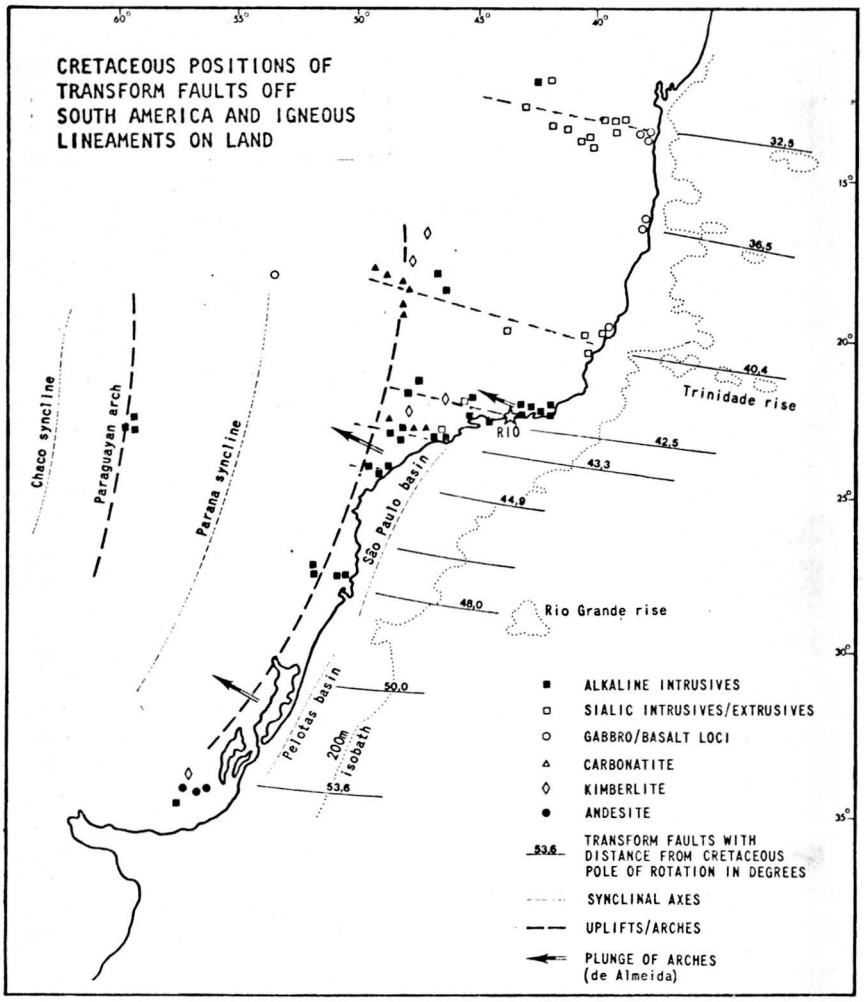

Fig. 65: Correspondence between transform faults as proposed by Francheteau and Le Pichon (1972) and igneous complexes along the east coast of South America. Structural elements symplified from de Almeida (1972).

6.4 EVIDENCE FROM OTHER CONTINENTS

6.4.1 India

Investigations in north-western India (Rao, 1970; Sukheswala and Avasia, 1971) revealed the occurrence of a large number of intrusions of alkaline rocks in an area dominated by the presence of great volumes of Deccan plateau basalt. Mesozoic carbonatite complexes occur at Amba Dongar and Udiapur. The Deccan volcanism has been dated at 50-70 m.y. whereas the alkaline/carbonatite magmas are considered to have been emplaced at a later date, viz. 37,5 m.y. (Sukheswala and Avasia, op.cit.). As in the case of the Etendeka (South West Africa) and Serra Geral (Brazil) lavas and the opening of the South Atlantic, Deccan volcanism coincided with the date proposed for the breakaway of the Indian sub-continent. Figure 66 illustrates the rifted position of India 35 m.y. ago and the proposed

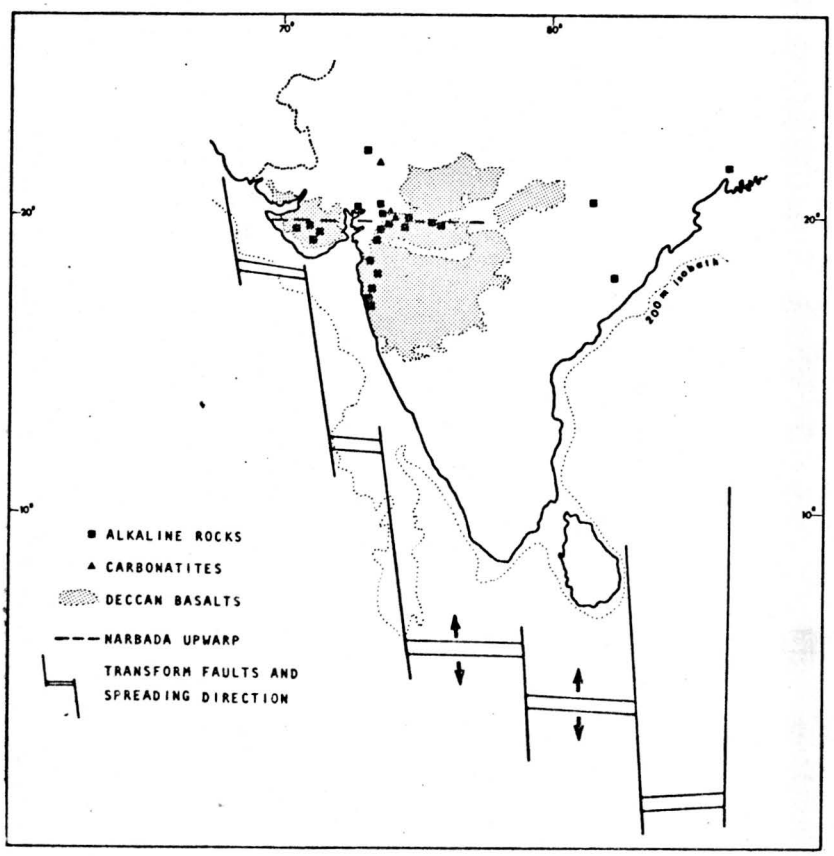

Fig. 66: Alkaline and carbonatite occurrences in India (Rao, 1970; Sukheswala and Avasia, 1971) and the position of transform faults as proposed by McKenzie and Sclater (1973).

transform faults along which it drifted northward (McKenzie and Sclater, 1973). Some of the Mesozoic alkaline/carbonatite occurrences in India were emplaced along a N-S zone situated directly in line with a major fracture zone. It is furthermore significant that the carbonatite complexes occur inland (Amba Dongar, Newania) whereas alkaline and gabbroic rocks (Bassein, Koraput, Girdar Hills) are situated nearer to the coast.

It has been suggested (Sukheswala and Avasia, 1966) that the alkaline/carbonatite magmatism is associated with an upwarped zone which extends along the Narbada valley in a E-W direction. The situation thus seems to be very similar to that described for the other provinces where carbonatitic activity is located at the intersection of a zone of uplift and the continental extension of a transform fault. The only difference is that in this instance the transform direction runs parallel to the rifted coast-line and the upwarp normal thereto.

6.4.2 East Greenland

Brooks (1973) interpreted the rifting history of the Greenland-Europe block in terms of a mantle plume which is situated below Iceland today. He suggested the development of a triple junction above this plume where two of the arms, those which parallel the present-day coastline of East Greenland, became active while the third, situated along the Kangerdlugssuaq fjord, remained inactive. He further suggested that this fjord must have a tectonic control as it cuts across the highest part of a dome. The alkaline complexes situated along the fjord show characteristics which are quite similar to those of the Damaraland province. The magmatic rocks become more alkaline with increasing distance from the coast as tholeiitic lavas and basic intrusions are replaced by syenitic complexes near the middle of the fjord. In the innermost part of the fjord central volcanoes and ring complexes of ultramafic alkaline rocks and carbonatites have been discovered (Brooks, op.cit.). The correspondence between the magmatism and tectonic activity in this area and that along the southwest coast of Africa prompts the suggestion that Kangerdlugssuaq fjord is not a triple junction but a transform direction whose development was associated with alkaline magmatism on the continent.

6.4.3 North America

The Monteregian and White Mountain provinces are among the few North American alkaline provinces that could possibly be linked with modern plate tectonics. They follow linear directions oblique to the east coast of this continent.

Recently Foland and Faul (1977) suggested that the age correspondence and chemical affinities of these provinces indicate that they should be considered together. Isotopic ages for the intrusives show that most of the magmatic activity occurred during three distinct periods at about 230, 200-165 and 125-100 m.y. ago. This age pattern is similar to that of the South American and Angolan-South West African lineaments.

Most of the White Mountain intrusions were emplaced in the 160-200 m.y. interval which corresponds to the age (180 m.y.) proposed for the initial opening of the North Atlantic (Le Pichon and Fox, 1971). Six intrusives were emplaced earlier during the 230 m.y. period whereas three others are significantly older than the majority of White Mountain rocks. Towards the western end of the Monteregian province a number of alkaline intrusives occur which have been dated at 565 and 450 m.y. (Doig and Barton, 1968).

It thus appears that, as in Africa and South America, alkaline magmatism occurred along linear zones long before the onset of crustal separation and was controlled by a major deepseated crustal fracture. Such a lithospheric fracture probably determined the location of the Kelvin fracture zone, was reactivated during continental breakup and also served as a locus for magma generation during the subsequent movement of the continent. These ideas tie in with those of Foland and Faul (1977) who suggested that the ages of intrusions from the White Mountain and Monteregian provinces are consistent with the hypothesis that these provinces formed along the continental extension of a transform fault and that the times of major plutonic magmatic activity could be related to times of significant changes in the opening of the North Atlantic.

There is also a change in the petrological nature of the complexes towards the interior (Christopher, 1960). Basic and granitic complexes (Tatnic Hills, Alfred, Agamenticus, etc.) occur near the coast and are followed deeper inland by complexes of a more alkaline nature (Pleasant Mountain, Red Hill, Abbott Mountain, etc.). Carbonatitic (Oka) and kimberlitic diatremes occur in the Monteregian igneous lineament; their location (Fig. 67) generally corresponds with the upwarp axis as proposed by Burek (1972), the crest of which is marked by the St. Lawrence rift.

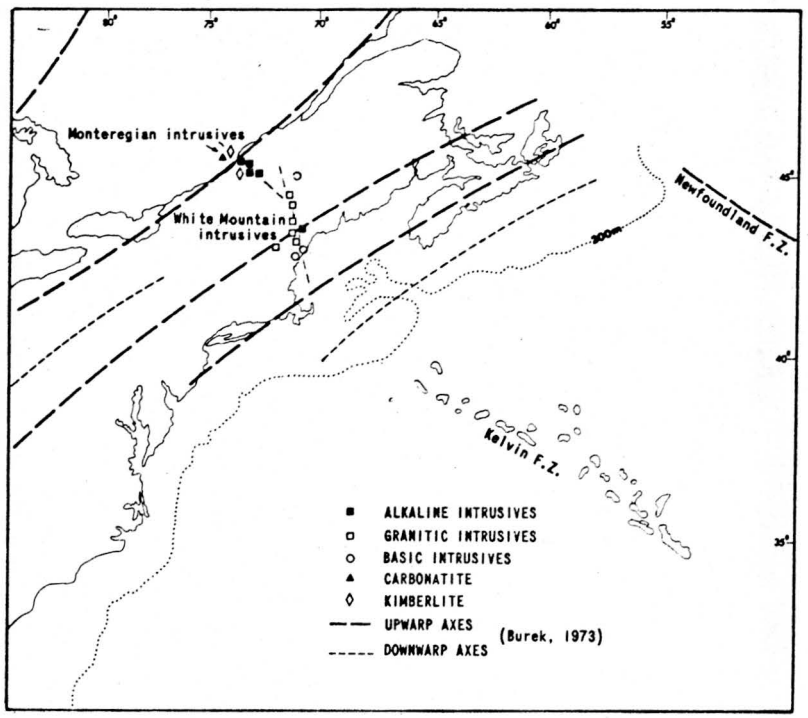

Fig. 67: Correspondence between the Monteregian and White Mountain igneous lineaments and the Kelvin fracture zone (New England seamount chain). Indicated also is the change in petrology along these lineaments and the proposed warp axes of Burek (1973).

6.5 SUMMARY

It has been illustrated that the position of a number of linear igneous provinces along the south-west coast of Africa can be correlated with unique fracture zones which offset the mid-oceanic ridge and that a similar situation might apply for such provinces in Greenland, India as well as South and North America.

These provinces generally exhibit a change in composition from the margin of the continent towards the interior. Basic complexes are found near the coast whereas further inland the complexes become alkalic and/or carbonatitic. In Angola, South West Africa, North and South America kimberlitic pipes are situated on the inland extension of most of these lineaments and may still be discovered in similar environments elsewhere.

CONTENTS PAGE

7 PETROGENESIS

7.1 INTRODUCTION

Alkaline rocks occur in a variety of petrological associations and their origin has been ascribed to processes such as magmatic differentiation (Von Eckermann, 1948; Macdonald, 1974), assimilation (Shand, 1945; Barker and Long, 1969), anatexis of the mantle or crust (Harris, 1974; Bailey, 1977), volatile action (Curry, 1970; Kogarko, 1974), liquid immiscibility (Philpotts, 1976) and metasomatism (Borodin and Pavlenko, 1974).

Likewise, the origin of carbonatitic rocks has been a major point of controversy among petrologists. The early ideas of Brögger (1921), Daly (1933) and Shand (1945) whereby the anatexis of limestone could result in a carbonatitic magma were accepted by Van Zijl (1962) in his study of the Kalkfeld and Okorusu com= plexes. Verwoerd (1967) concluded that whereas limestone assimilation may have played a part in the Damaraland province, it fails to account for the majority of carbonatite occurrences. Most authors nowadays reject this hypothesis. A popular view among Soviet geologists is that carbonatitic magmas are the products of metasomatic exchange reactions whereby the major components Ca, Mg, Fe, etc., are removed from solid silicate rocks by carbonate solutions rising from deep-seated magma chambers (Vlasov, 1968, p.228). However, the majority of non-Soviet geologists believe that carbonatite magmas are of primary origin (Holmes, 1958; Koster van Groos, 1975), or that they are late products resulting either from liquid immiscibility (Wyllie, 1966; Ferguson and Curry, 1972; Rankin and Le Bas, 1974) or from fractional crystallization of CO_2-rich alkaline magmas (Cooper, et al., 1975).

7.2 THE ALKALINE ROCKS

It has been suggested (Chapter 6) that the alkaline-carbonatite magmatism in Damaraland occurred where a pre-existing crustal weak zone was transsected by an upwarp axis which developed parallel to the rifted coastline. Pressure relief and partial melting occurred along the weak zone during plate movement and volatiles were fluxed into the upwarped area causing a carbonated alkaline (nephelinitic) magma to develop. This magma is regarded as the primary source from which different magma types developed to form the alkaline-carbonatitic complexes.

7.2.1 Comparison with the Qz-Ne-Kp system

The evolution and crystallization paths of liquids from which syenites and nepheline syenites crystallize can conveniently be described in terms of the Qz-Ne-Kp system. The main features of this system have been described by Tuttle and Bowen (1958), Fudali (1962), Hamilton and MacKenzie (1965) and Edgar (1974). Very important is the fact that the alkali-feldspar join (Or-Ab) in this system has been shown to be a thermal barrier which prevents the passage of quartz or nepheline normative liquids to the other side. As shown in Fig. 68D a thermal valley exists on the liquidus surface in the feldspar field of this system. Liquids resulting from fractional crystallization of undersaturated alkaline magmas thus ought to have compositions plotting very close to this low temperature valley. The alkaline rocks of Kalkfeld plot near the eutectic point whereas those of Etaneno and Okorusu define a trend along the low temperature trough (Fig. 68). This suggests that a process of crystal-liquid equilibrium was involved in their genesis and that fractional crystallization probably played and important role during their solidification. However, these rocks are characterized by some major and minor element variations which do not conform to uniform trends explicable in terms of simple fractionation schemes. In stead, the data often show a wide spread rather than a trend (see Chapter 2). This feature appears in many descriptions of alkaline complexes and has not been explained adequately. It must be remembered that alkaline magmas are usually accompanied by extensive alkaline metasomatism resulting from fluids in equilibrium with the alkaline magma. The extraction of various elements (especially Na) from these melts certainly affected their course of crystallization and, coupled with the influence of fluids on solidified portions, might be responsible for the confusing variations displayed by rocks from such complexes.

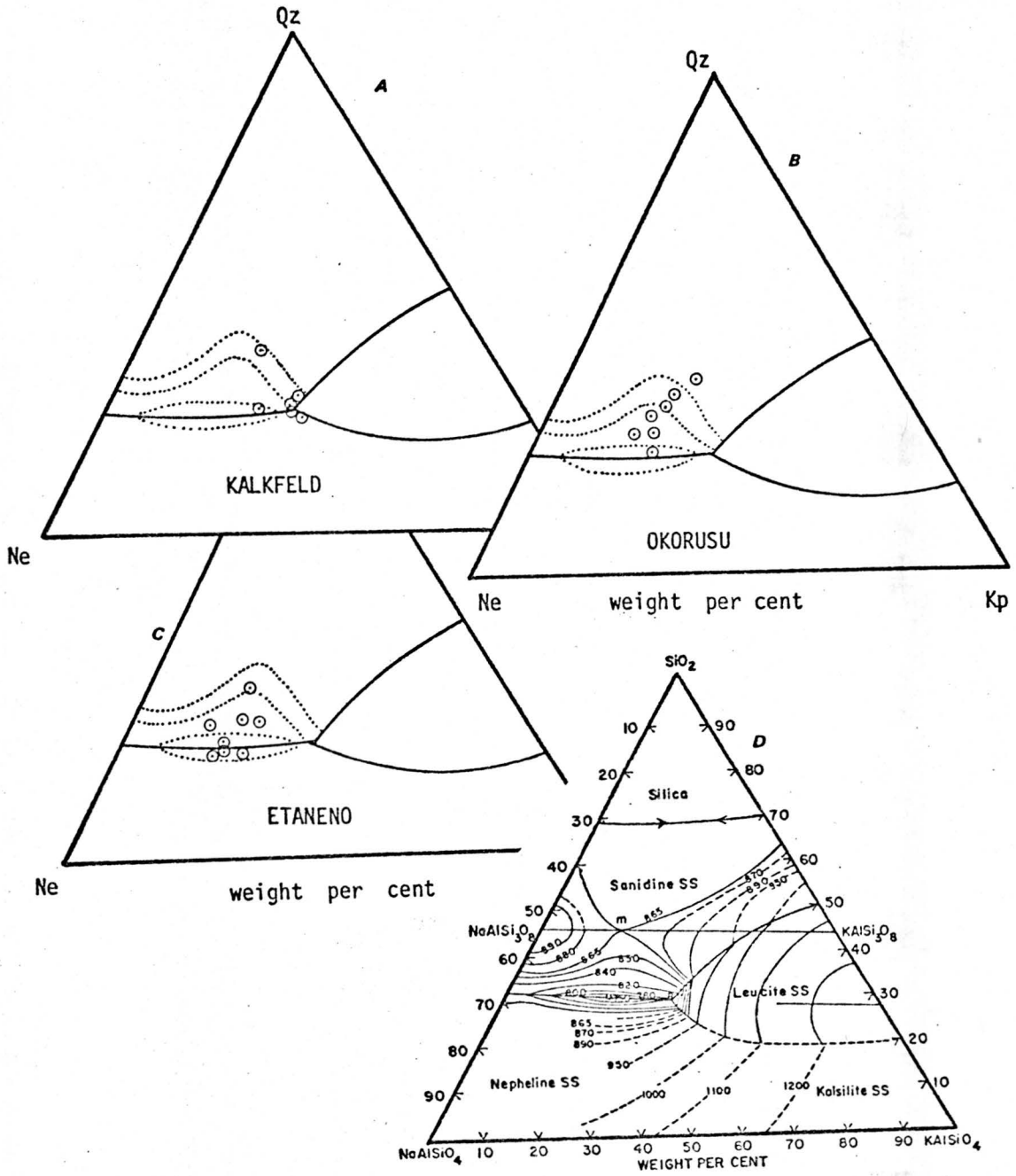

Fig. 68: Normative Qz-Ne-Kp diagram of syenites and nepheline syenites from Kalkfeld, Okorusu and Etaneno. Diagram D represents the experimental system Ne-Ks-Sil at 1 kb P_{H_2O} (after Hamilton and MacKensie, 1965).

7.2.2 The Etaneno peralkaline magmas

The alkaline rocks associated with the Damaraland alkaline complexes are all undersaturated. The oversaturated bostonite dykes of Kalkfeld are exceptional and may not belong to the main period of alkaline magmatism. They could represent Late Karoo magmatism or might even be considered remobilized fenites. Nearly all the alkaline rocks from this province exhibit a deficiency of Al_2O_3 with respect to Na_2O, K_2O and CaO. This is illustrated by the presence of diopside and/or wollastonite in their CIPW norms. The development of a peralkaline residue from a magma exhibiting such a molar deficiency is possible through a number of fractionation schemes. The "plagioclase effect" (Bowen, 1945) or the fractionation of biotite (Carmichael, 1967), Al-rich pyroxene (Schairer and Yoder, 1960) spinel, garnet or Al-bearing iron-oxide (Bailey and Schairer, 1966) or a non-stoichiometric alkali-feldspar (Luth and Tuttle, 1966) could all result in such liquids.

At Etaneno the core nepheline syenite which is regarded as the earliest intrusive phase carries plagioclase (An_{35-65}) that is sometimes rimmed by an alkali-feldspar with the composition of anorthoclase. This suggests that the plagioclase effect might have been operative in depth causing the peralkaline nature of the rest magmas. Further feldspar and nepheline fractionation maintained this trend resulting in the highly peralkaline nature of the main intrusions. Although the Qz-Ne-Ks system is useful to describe trends in most alkaline rocks it is not strictly applicable to peraluminous and peralkaline rocks. Bailey and Macdonald (1969) have therefore advocated the use of plots based on the molecular proportions of SiO_2, Al_2O_3, Na_2O and K_2O to indicate feldspar fractionation. Rocks which originate solely by such fractionation would plot on a line that originates at a point indicating the composition of the fractionating feldspar. Such a plot has been constructed for the Etaneno rocks (Fig. 69). The alkali-feldspar phenocrysts plot on the Al-deficient side of the diagram. This is ascribed to the relatively poor precision of the Na analyses. The enlarged scale of the diagram further amplifies this feature. A real deficiency in Al in these feldspars is not favoured. It is further more obvious that fractionation of alkali feldspar could not have caused the trend as displayed by these intrusions. The three rock types which are regarded as representative of the earliest magmas, i.e. the dark nepheline syenite dykes, the core nepheline syenite an the coarse-grained nepheline syenite, plot below the albite-nepheline cotectic in this system. Coprecipitation of a Ca-rich feldspar and

nepheline, the latter being the dominant fractionating phase, thus seems to have resulted in the trend illustrated in Fig. 69.

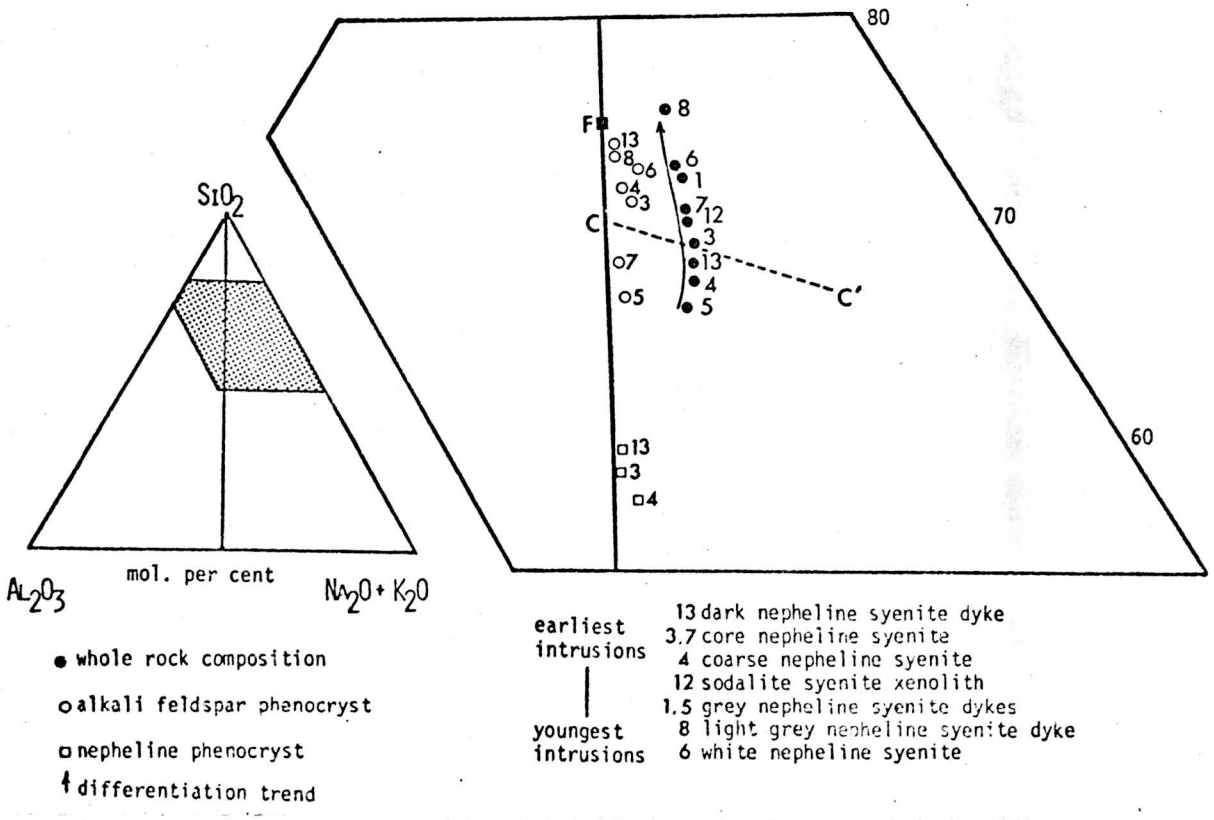

Fig. 69: Analyses of the Etaneno peralkaline nepheline syenites and their phenocryst phases plotted in the SiO_2-Al_2O_3-(Na_2O + K_2O) diagram.
F = eutectic feldspar composition.
C—C´albite-nepheline cotectic from Macdonald (1974).

If these intrusive pulses were drawn from a crystallizing magma at depth a study of the phenocrysts they carry, should provide an indication of their relative age relationships. A useful picture emerges when the various rock types are arranged in order of decreasing K/Rb ratio of their feldspar phenocrysts. The following order of decreasing age is indicated: dark nepheline syenite dyke; core nepheline syenite; coarse-grained nepheline syenite; grey nepheline sye= nite; white nepheline syenite and a light grey nepheline syenite dyke (Fig. 70).

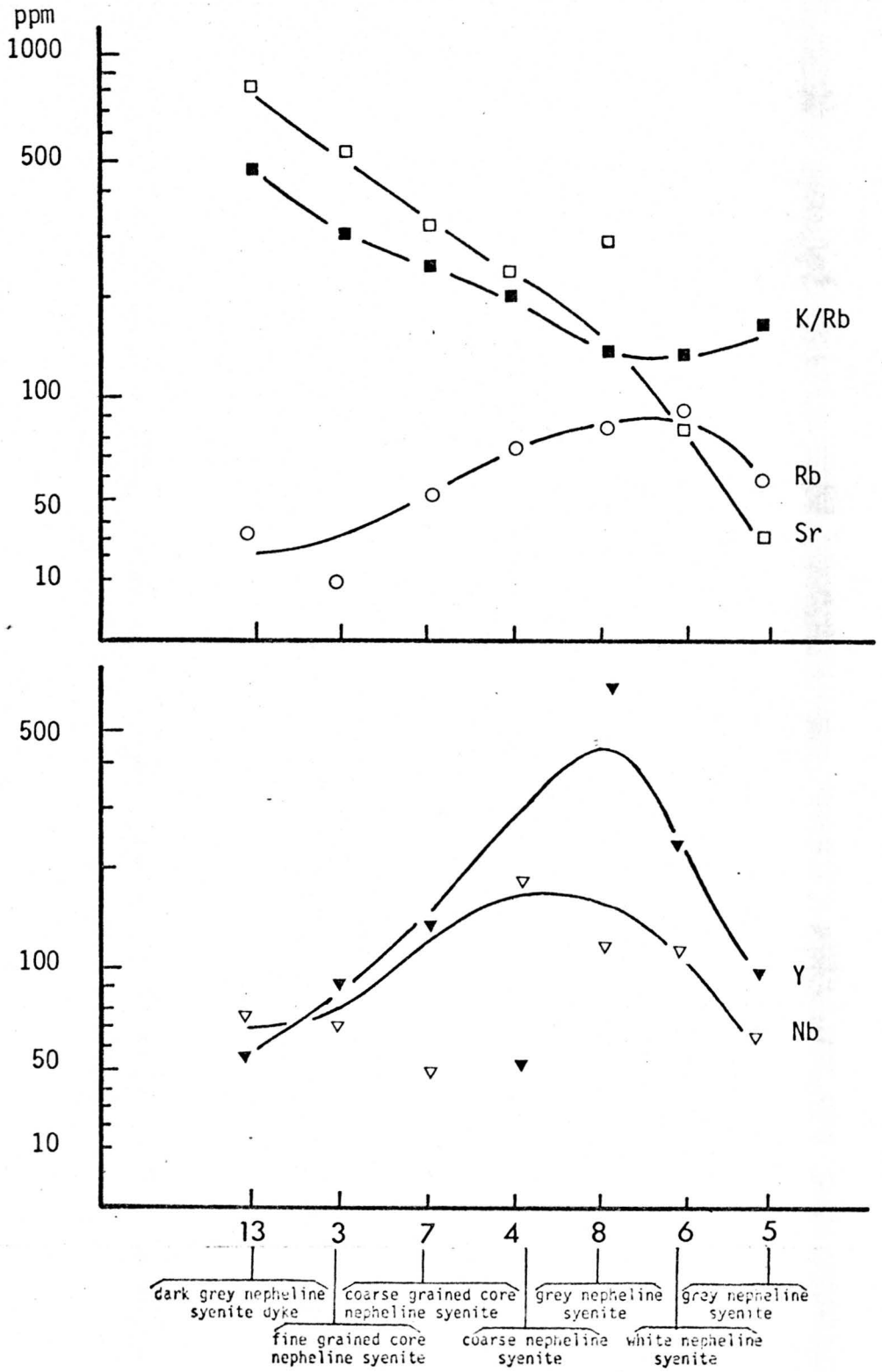

Fig. 70: Variation in K/Rb and trace element content of the alkali feldspar phenocrysts of the main rock types from Etaneno.

The dark grey nepheline syenite dyke which carries an alkali feldspar with a high K/Rb ratio probably represents and undifferentiated portion of the earliest magma. The suggested early intrusion of the plug of core nepheline syenite is supported by the composition of the feldspar from its fine and coarse-grained facies (Fig. 70).

It is significant that the feldspar of the coarse nepheline syenite has a K/Rb ratio which also indicates an early crystallization history. This is supported by the Sr, Rb and Y values of the feldspar that conform to the variation trends shown in Fig. 70. The suggestion of Verwoerd (personal communication) that this intrusion represents an injected cumulate fraction is therefore in agreement with its feldspar composition. The alkali feldspar of the grey and white nepheline syenite units have K/Rb and trace element values which are similar and which indicate a somewhat later stage of crystallization. This fits the field evidence which suggests a gradational relationship between these two rock types, the white variety having solidified slightly later.

Alkali feldspar from a cross-cutting grey nepheline syenite dyke has a K/Rb ratio somewhat anomalous for a late intrusion. This dyke could, however, represent a portion of an earlier magma which escaped the major phase of differentiation.

7.2.3 The enigmatic sodalite syenites

The origin of the sodalite syenite which occurs as xenoliths in the grey and white nepheline syenite units remains problematic. The variable nature of the grain size, texture and mineralogy of these xenoliths (Verwoerd and Retief, unpublished) is confirmed by the difference between the two analyses available for this rock type (see Appendix, Table 16). Its major element content is similar to that of the more differentiated rock types (Fig. 12).

The genesis of sodalite-rich rocks have recently been ascribed to immiscibility processes whereby an aqueous-saline liquid separates from a siliceous magma. According to the phase diagram (Na, K)$AlSiO_4$-(K, Na)$AlSi_3O_8$-(Na, K)Cl, crystallization of certain compositions situated in the field of primary carnegieite will result in the separation of a chloride-rich fluid (Kogarko and Ryabchikov (1969). This fluid has an extremely low viscosity and will migrate into structurally favourable parts of the magma chamber, where, with further cooling it

may react with primary nepheline to form sodalite. It is considered that portions of such a reaction product were later picked up by various surges of alkaline magma and now appear as xenoliths. Such an origin accounts for their presence in the early grey syenite as well as the somewhat later white nepheline syenite units. The variation in mineralogy, texture and volatile content of these xenoliths probably depends on the time when the chloride-rich fluid were incorporated in the upward moving nepheline-bearing magma.

The development of a sodalite-enriched portion of the melt as a result of the flotation of sodalite crystals, as suggested for the origin of the naujaites of Ilimaussaq (Sørensen, 1969) is not favoured here because of lack of textural evidence and because the Etaneno magmas were relatively dry and thus highly viscous. It may be that the absence of carbonatitic and fenitic rocks at this complex has some bearing on the development of an early water- and volatile-rich fluid as proposed here.

7.3 THE CARBONATITIC ROCKS

7.3.1 Chemical evidence

Koster van Groos (1975) argued that if carbonate magmas are the late stage products of a fractionation process of alkaline/ultrabasic magmas, carbonatites would be strongly enriched in SrO and the ultrabasic rocks depleted in SrO, relative to CaO. The SrO/CaO ratio of all the Damaraland carbonatites are similar to, and in a few cases even less than that of their associated alkaline rocks. This supports the thesis that these carbonatite magmas coexisted with an alkaline silicate magma and that if they developed as a late-stage fractionation product, the parent magma is not represented among the rock types analysed. It can be seen from Fig. 71 that the SrO/CaO ratios of the alkaline and carbonatite rocks contitute two trends which both increase with differentiation and age of the rocks. This would be expected if these two rock series developed along two separate fractionation paths.

Available analyses of the rock types present in die Damaraland alkaline complexes show a gap between SiO_2 contents of 15 and 40 per cent. A plot of CaO + MgO versus SiO_2 of all the available analyses (Fig. 72) show that the carbonatitic rocks fall on a trend well separated from that of the alkaline rocks. This

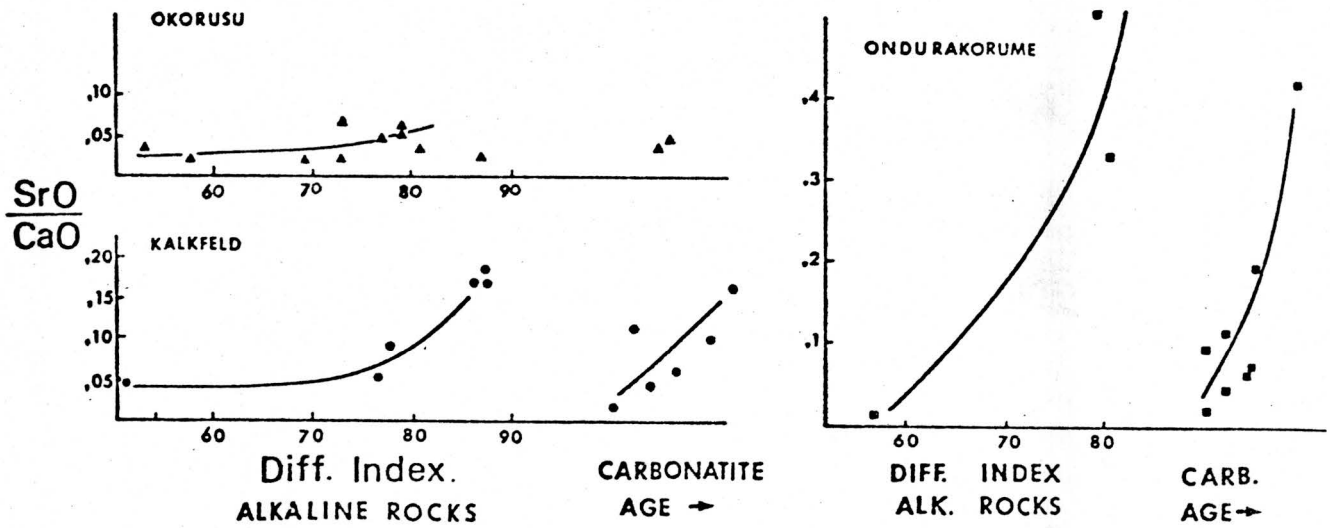

Fig. 71: SrO/CaO ratio (wt%) of the alkaline and carbonatitic rocks of Kalkfeld, Okorusu and Ondurakorume plotted against the differentiation indices and inferred age of the rocks respectively. Note the similarity of the ratio for alkaline and carbonatitic rocks.

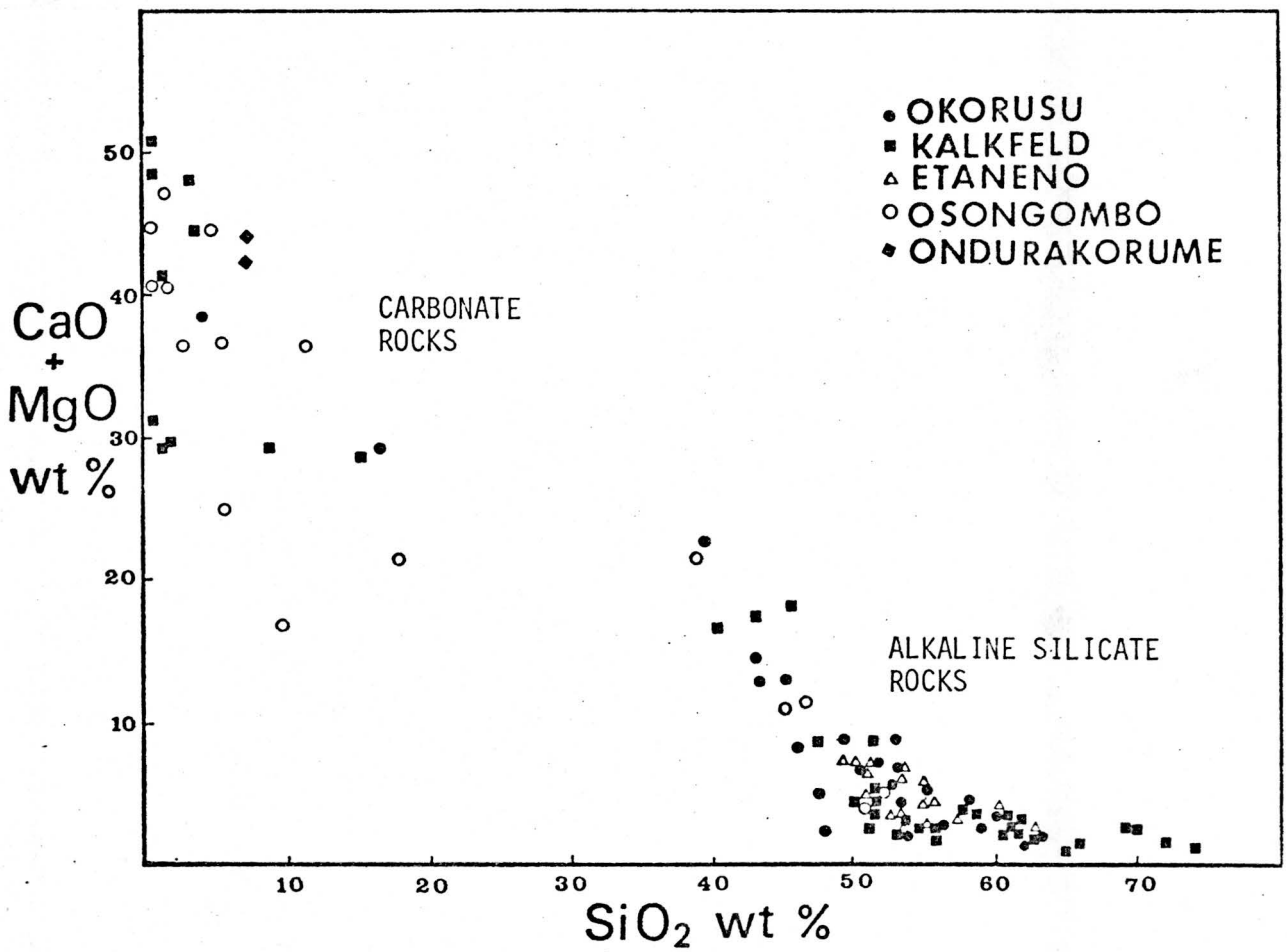

Fig. 72: Variation of CaO + MgO with SiO_2 (wt.%) of all available analyses of rocks from the alkaline /carbonatite complexes of Damaraland.

again provides evidence that the carbonatitic rocks are not the end-product of an alkaline magma which underwent fractional crystallization. The geochemical observations would however, be in perfect agreement with a process of liquid immiscibility giving rise to two differentiating liquids.

In Chapter 3 it was shown that the composition of the carbonatitic rocks of the Damaraland complexes vary in the order of their intrusive age along a trend towards Mg enrichment. This is considered to indicate that the rocks represent a liquid line of descent for the carbonatitic magmas in this province.

7.3.2 Petrological evidence of liquid immiscibility

Field and laboratory evidence indicate that immiscibility between alkali-rich silicate and calcium carbonate melts occurs in nature. The occurrence of leucocratic, sometimes carbonate-rich, ocelli in monchiquitic and camptonitic dykes at Callander Bay has been ascribed to a process of liquid immiscibility (Ferguson and Curry, 1971). Phillpotts (1976) attached a similar origin to the feldspar and carbonate-rich ocelli which occur in a variety of alkaline rocks from the Monteregian province. Experiments by Koster van Groos (1975) demonstrated that there is a miscibility gap between silicate and carbonate liquids at 10 kbar in the join $NaAlSi_3O_8$-$CaAl_2Si_2O_8$-Na_2CO_3-H_2O and that it extends into systems containing MgO, K_2O and Fe_2O_3. Heating stage experiments on fluid inclusions in apatite from ijolites also showed that liquid immiscibility between silicate and carbonate melts occurs in nature (Rankin and Le Bas, 1974). Recently Le Bas (1977) concluded that a high temperature (> 800^{o}C) liquid immiscibility split between ijolitic and alkali-rich carbonate melts is the most likely cause of the carbonatite-nephelinite associations of central Africa.

Irregular and rounded globules consisting mainly of calcite, alkali feldspar, analcite and phlogopite occur in dark, fine-grained alkaline rocks at Okorusu and Kalkfeld. Van Zijl (1962) described these globules as amygdales occuring in nephelinite. During a recent field investigation the Okorusu "nephelinites" were identified as hypabyssal intrusions rather than lavas. At Ondurakorume calcite-apatite-rich globules occur in a fine-grained chloritic rock. Verwoerd (1967) described these globules as "pisolites" similar to those occurring in the metacarbonatite and biotite metabeforsite of Goudini. A re-investigation of these occurrences became necessary in view of the liquid immiscibility origin suggested for "ocelli" with a similar appearance and composition.

7.3.2.1 Okorusu

During a field visit in 1976 it was discovered that carbonatitic rocks are more widespread at Okorusu than indicated on Van Zijl's map. Sövites as well as sövitic breccias were found in close association with globule-carrying alkaline dykes, especially in the area previously mapped as nephelinite. The groundmass minerals of these dykes are aegirine, phlogopite, olivine, calcite, K-feldspar, kaersutite, analcite and smaller amounts of apatite, magnetite, sphene and chlorite. This mineralogy is very similar to that of the monchiquitic dykes at Callander Bay (Ferguson and Currie, 1971). The Okorusu dykes vary in width from 1-3 metres and carry two varieties of leucocratic globules. The small and spheroidal variety (1-2mm in diameter) is comprised mainly of calcite and analcite whereas the larger type (3-10mm in diameter) exhibits irregular outlines and contain larger proportions of phlogopite and feldspar. The globules of a specific outcrop are generally of one type only. They are irregularly distributed throughout the dykes but are sometimes concentrated in zones parallel to the walls.

The shape of the globules from these dykes is particularly interesting. The smaller calcite-rich ones are normally spherical while some cross-sections suggest 2 or 3 globules in the process of coalescence (Fig. 73 b and c). On the other hand the larger silicate-rich globules exhibit an irregular form which in some cases suggest that they were in a process of diapiric motion. Their tops are generally flattened which might be interpreted as the result of a host liquid becoming too viscous to allow further upward migration. Other globules leave no doubt that they constituted a separate fluid phase. Their cuspate boundaries indicate that their surface tension was less than that of the host silicate liquid. Veins of a similar composition occur in samples where globules tend to coalesce.

Small round globules from sample Oku 45 consist of 25% sodalite, 55% calcite, 10% feldspar, 10% phlogopite (determined by point count analyses of 50 globules in thin section). Minor accessories identified by electron microprobe include magnetite, aegirine, sphene and strontianite (Fig. 74). The calcite crystals contain dustlike inclusions of strontianite aligned along crystallographic directions and are therefore considered to represent an exsolved phase. Phlogopite generally crystallized at the margins of these globules and is distinctly zoned with euhedral boundaries. Phlogopite with a similar composition and zoning (see microprobe analyses, Table 10) occur in the groundmass.

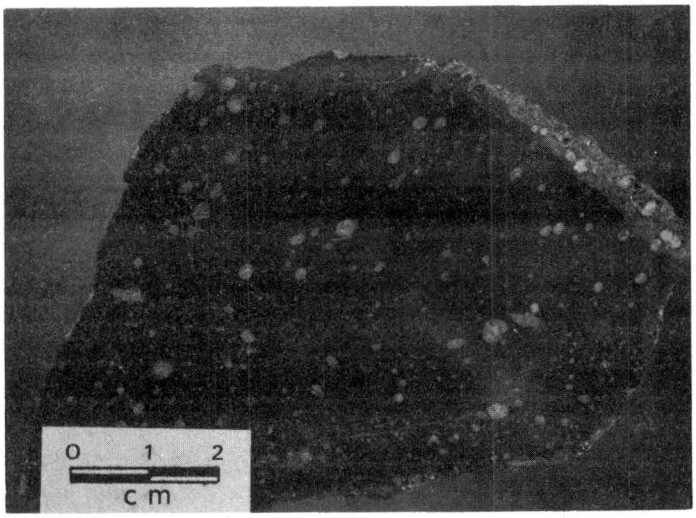

Fig. 73(a): Rounded and oval globules set in a dense matrix of pyroxene, nepheline(?), analcite, magnetite, biotite and olivine. (Oku 43).

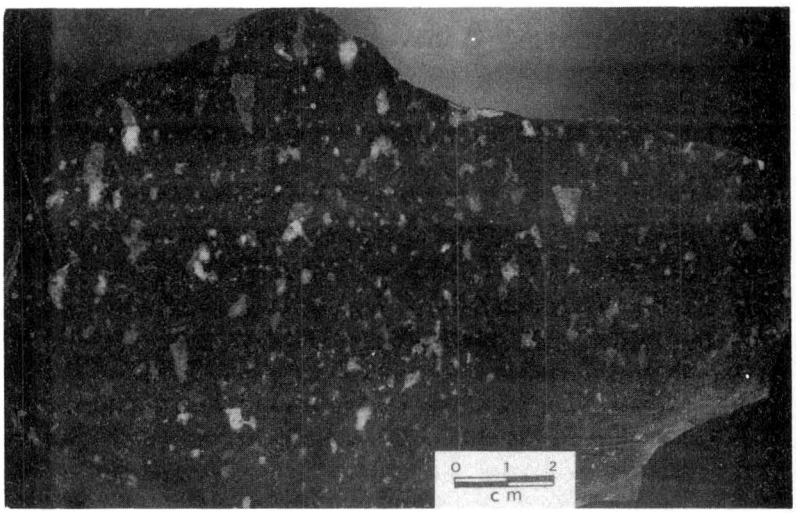

Fig. 73(b): Calcite-analcite-feldspar-phlogopite globules with cuspate boun= daries and flattened tops in monchiquite from Okorusu. (Oku 44).

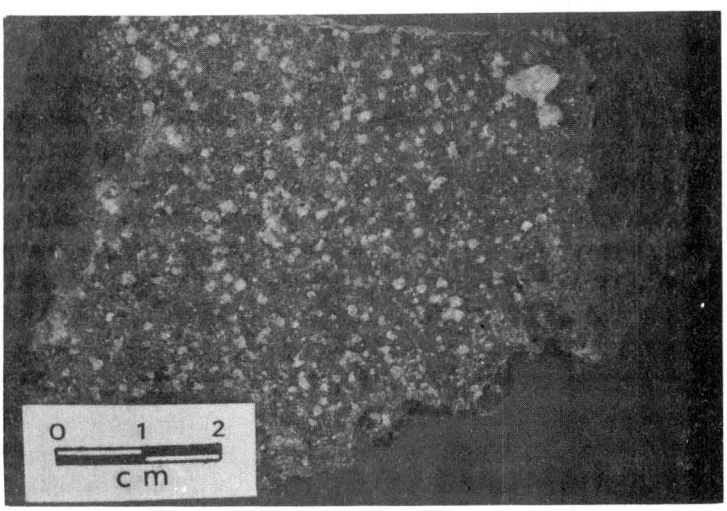

Fig. 73(c): Carbonate-rich globules crowding a lamprophyre (cascadite) which consists of phlogopite, olivine and augite phenocrysts set in a matrix of alkali feldspar, analcite, Fe oxides and pyroxene. (Oku 45).

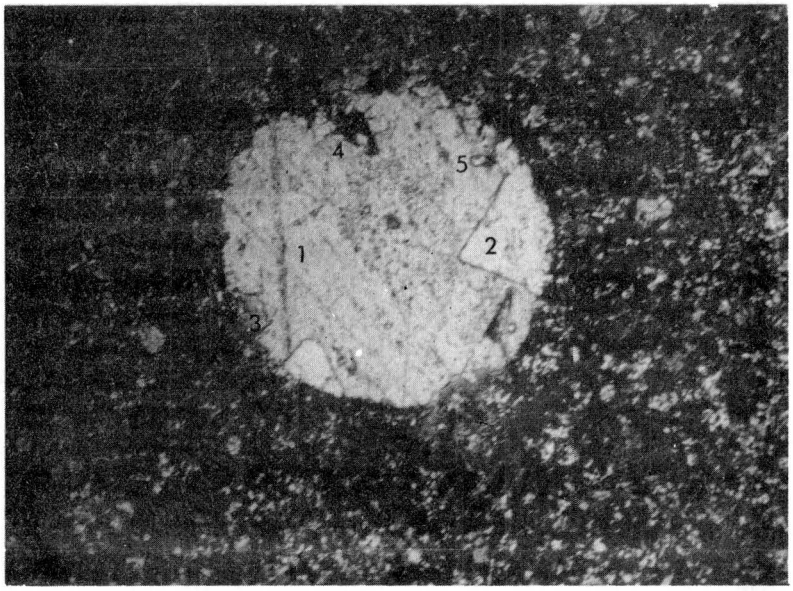

Fig. 74: Globule consisting of calcite(1), sodalite(2), phlogopite(3), Fe-oxides(4) and strontianite(5) in fine-grained monchiquite from Okorusu (plane polarized light, x15).

TABLE 7: Microprobe analyses of some of the major phases of carbonate-rich globules in basic alkaline dykes

	Oku 44 (cascadite)			Oku 45 (monchiquite)		
	phlogopite	albite	sodalite	phlogopite	augite	sodalite
SiO_2	40,56	68,23	38,09	36,88	49,22	38,66
TiO_2	2,13	-	-	2,29	1,30	-
Al_2O_3	10,74	20,19	32,08	10,36	4,63	31,04
FeO tot.	15,85	-	-	17,53	7,04	,64
MnO	1,15	-	-	1,13	0,12	-
MgO	14,52	-	-	17,15	12,54	-
CaO	-	-	-	0,12	24,34	,15
Na_2O	-	-	24,55	0,19	0,48	23,8
K_2O	10,23	-	0,01	10,23	0,11	0,67
Cl	n.d	-	8,10	n.d	n.d	7,31
			102,83			102,31
O≡Cl			1,86			1,68
Total	95,17	100,04	100,97	95,88	99,85	100,63

The requirement of identical composition for the crystals forming in two im= miscible liquids has been stressed by Bowen (1928). However, in this case the outer edges of the phlogopite crystals underwent resorption by the silicate liquid while those in the carbonate globule remained perfectly in equilibrium. Crystals which transect the boundary between globlue and matrix illustrate this further. During cooling these crystals retained their euhedral form whereas those parts of the crystal located in the silicate liquid were resorbed (Fig. 75). It can not be expected that equilibrium will be maintained during the solidifi= cation history of the two liquids, especially if crystallization fractionation occurred in either or both of the two liquids. In fact, Roedder (1978) sug= gests that identical composition of phases are indicative of an immiscibility process only when the crystals are present in glass.

The larger irregular globules from rock sample Oku 44 exhibit a similar minera= logy as the smaller ones from sample Oku 45, except for a greater K-feldspar con= tent and the appearance of barite, ilmenite and analcite. The composition of some of these phases is given in Table 10. The silicate and carbonate minerals are dis= tributed throughout the globular mass (Fig. 76). They do not, as one might ex= pect in amygdale formation, occur as a few large crystals nucleated on the walls.

Some globules suggest that a stratified texture i.e. feldspar at the bottom, cal= cite and analcite at the top might be present (Fig. 77). Such a texture has been interpreted by Phillpotts and Hodgson (1968) as evidence for immiscibility. At Okorusu these features are too limited and original orientation of the speci= men too uncertain to be of positive value.

The trace element content of these globules are significant. Strontianite oc= curs as sparse but relatively large grains in some of these globules. Barite is present in amounts of less than 5% in these globules. A Sr-Ba rich carbonate phase also exsolved as minute blebs from the calcite. This is very atypical of gas-filled vacuoles and strongly suggests that the globules represent a melt of carbonatitic affinity.

Apatite was not identified in these globules. Its absence is surprising as it does occur in the groundmass in the form of small interstitial grains. Fe-Ti oxide phases are ubiquitous. Orthoclase as well as plagioclase sometimes exceed 30% by volume in thin section. Aegirine and an amphibole are minor phases. In optical properties they are similar to phases occurring in the groundmass - a feature verified by qualitative microprobe analysis.

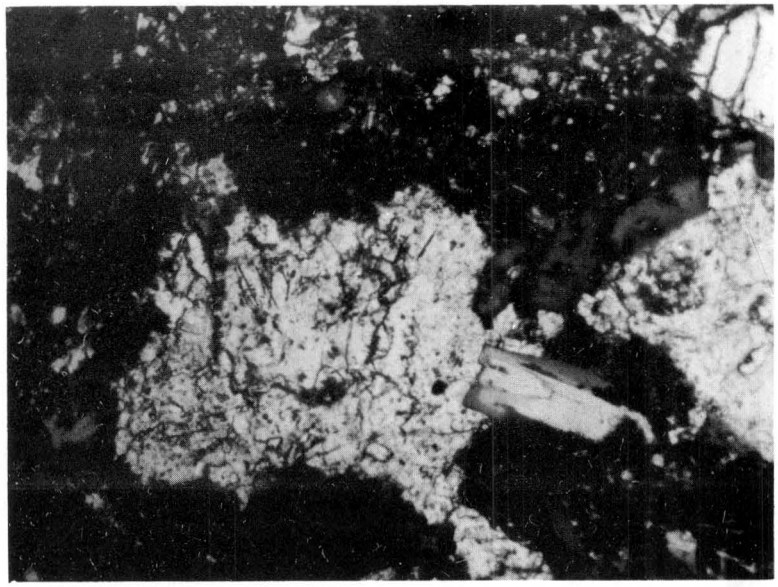

Fig. 75: Zoned phlogopite crystal transecting the boundary between matrix and globule. Note the euhedral boundary of the crystal in the carbonate globule and its resorbed edges in the matrix. (plane polarized light, x15).

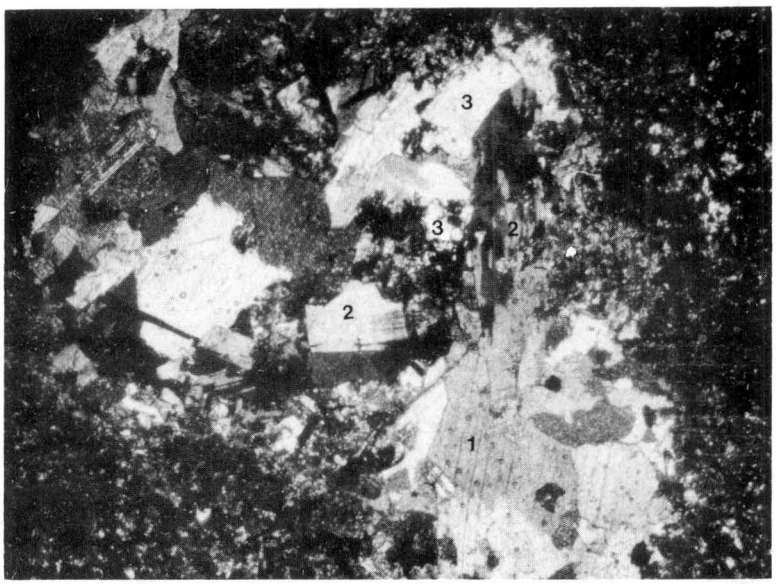

Fig. 76: Globule from sample Oku 44 suggesting a coalesced form. Calcite(1), alkali-feldspar(2), barite(3), analcite and Fe-oxides (dark) are distributed throughout the globule. (crossed nicols, x20).

Fig. 77: Concentration of alkali-feldspar, phlogopite and Fe-oxides on the base and rim of a globule suggests crystallization (or density) fractionation within the globule. The dark area in the globule consists of analcite. (crossed nicols, x25).

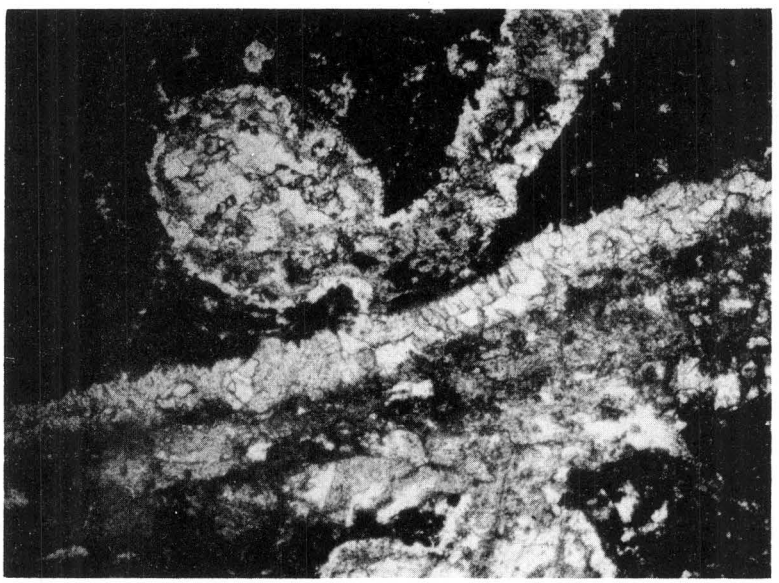

Fig. 78: Coalescence of carbonate-feldspar globules and a vein of similar composition. A thicker vein showing a zoned structure transects the earlier one. (plane polarized light, x15).

7.3.2.2 Ondurakorume

Highly altered khaki-coloured chloritic rocks, the so-called micaceous sövites, occur in close association with irregular bodies of pure sövite at Ondurakorume. These chloritic rocks sometimes carry small spherical structures which consist of hydrobiotite, calcite and smaller amounts of apatite. The grondmass consists of very fine-grained chlorite with very small crystals of biotite, apatite, aegirine and magnetite octahedra in lesser amounts. Coarses patches of calcite and veins of calcite and apatite occur throughout the rock.

It is suggested here that these glimmerites represent the altered products of ijolitic or pyroxenitic rocks known to occur in close association with pure sövite at many localities, e.g. Jacupiranga, Spitzkop. If this is true then all three major Damaraland carbonatite complexes would contain pyroxenitic-ijolitic rocks carrying irregular and/or spheroidal carbonate-rich globules.

Also present at Ondurakorume are olivine dolerite dykes containing spherical blebs of calcite, spherulitic chlorite, zeolites and analcite. The texture of these bodies (Fig. 79) differs markedly from those previously described and they were probably correctly interpreted as amygdales (Verwoerd, 1967).

Fig. 79: Amygdale consisting of calcite, spherulitic chlorite, zeolites and analcite in olivine dolerite dyke from Ondurakorume. (plane polarized light, x15).

7.3.2.3 Kalkfeld

Van Zijl (1962) described the occurrence of calcite-zeolite-rich amygdales in altered biotite-glimmerite dykes and in an extremely fine-grained rock consisting predominantly of plagioclase and subordinate amounts of calcite, biotite, magnetite, pyroxene and amphibole. A handspecimen from Van Zijl's collection showed round globules (1-3mm in diameter) consisting mainly of calcite and analcite with minor amounts of magnetite and phlogopite set in a dense black matrix comprised of pyroxene, magnetite, calcite, phlogopite and chlorite. Veins consisting of calcite, plagioclase and analcite cut accross the specimen. The mineralogy and appearance of this sample is similar to some of the Okorusu rock types which also carry carbonate-rich globules.

7.4 SUMMARY

The nature of the globules described above prompts one to suggest that they represent immiscible droplets which separated during the early crystallization history of the alkali melts. The more volatile nature of the carbonate liquid not only caused it to remain liquid longer than the siliceous host from which it exsolved but also allowed its upward migration. Melting experiments by Koster van Groos and Wyllie (1963, 1966) on silicate-carbonate systems and by Roedder (1954) on the fayalite-leucite-silica system provide information that may be applicable to the rocks in question. Roedder showed that when the crystallization path enters the two liquid fields in the silicate system from the fayalite side, this mineral crystallizes until one of the two liquids are solidified. This concept has been applied by Ferguson and Currie (1971) and is equally applicable in the Damaraland rocks where it can be assumed that immiscibility must have occurred after the crystallization of olivine as this mineral is not present in the globules. Pyroxene and Fe-Ti oxides which crystallized in both liquids were in equilibrium with each other as the composition of these phases in the globules and groundmass has been shown by microprobe investigation to be similar. However, the composition of both liquids changed as they continued to solidify. In the case of the silicate portion disequilibrium between liquid and early formed crystals developed which resulted in the resorption of biotite phenocrysts (Fig. 77).

Although there is no direct evidence by which the development of carbonate-rich globules can be linked with the origin of the carbonatite magmas, the mere presence of such globules at the complexes under consideration and the chemical anomalies described earlier, suggest that an immiscibility process is by far the most likely explanation for the origin of the Damaraland carbonatites.

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8 CONCLUSIONS

A number of linear igneous provinces containing alkaline and carbonatite intrusions are situated along the southwest coast of Africa. Their age, distribution and petrographic features differ markedly from those of the central African provinces and suggest that their development, unlike the latter, is connected with the rifting of Gondwanaland and the formation of new oceanic floor.

It has been demonstrated that the position of these igneous provinces can be correlated with unique fracture zones which offset the mid-oceanic ridge. The same relationship seems to hold for Mesozoic alkaline and carbonatite provinces from South and North America, India, Greenland and the Red Sea area.

Transform faults are believed to be initiated along existing weaknesses in the crust of a continent. Stresses that accompany plate movement are thought to be focussed in these weak zones, resulting in the partial melting of the lower crust and mantle. The igneous provinces generally exhibit a change in composition from the margin of the continent towards the interior. Ba= sic complexes are found near the coast whereas further inland the complexes become alkalic and carbonatitic. In Angola, South West Africa, North and South America kimberlitic pipes are situated on the inland extension of most of these lineaments and may still be discovered in similar environments else= where. The development of linear tensional zones along existing crustal fractures, coupled with the increased heat flow near the coast as a result of seafloor spreading are considered to be responsible for the development of normal and alkali-tholeiitic magmas at relatively shallow depths whereas further inland, partial melting occurred at deeper levels producing magmas of higher alkalinity. It is suggested that a series of undulations of the crust developed parallel to the line of separation, i.e. the rifted coast=

line. The development of central type carbonatite complexes were restricted to those areas where existing crustal fractures intersected these upwarps which served as zones of decompression into which volatiles have been fluxed. This led to the development of a carbonated nephelinitic magma which underwent a high temperature liquid immiscibility split on its way to the surface. The resulting ijolitic and carbonatitic fractions followed individual differentiation paths after their separation. The silicate melts differentiated mainly through feldspar and nepheline fractionation and coexisted with a Na-Fe-rich fluid which caused extensive pyroxene fenitization. The carbonatite melts differentiated towards rare earth- and volatile-rich fractions which were emplaced as rare earth-rich amphibole beforsite dykes (Ondurakorume) and as hydrothermal fluorite (Okorusu) and Fe-ore (Osongombe, Kalkfeld, Ondurakorume and Okorusu) deposits. The brecciation and feldspathization which occurred at these complexes are associated with K-CO_2-rich fluids which were in equilibrium with the carbonatite magmas.

But beyond the bright searchlight of science
Out of sight of the windows of sense
Old riddles still bid us defiance
Old questions of Why and Whence

W.C.D. Wethan

CONTENTS

APPENDIX

A. METHODS OF CHEMICAL ANALYSIS USED FOR ROCK SAMPLES AND MINERAL SEPARATES

1. X-ray fluorescence methods

A Philips PW1410 spectrometer was used for all X-ray fluorescence analyses that were done in duplicate by the method of Norrish and Hutton (1969). Major elements, except Na, were determined on fusion discs. Trace elements as well as Na were determined on pressed powder briqettes which were made from 4 gram of finely powdered (-300 mesh) material.

Analytical conditions for the major and trace element determinations are given in Tables 11 and 12. USGS and NIM rock standards were used for calibration and the values adopted are given (Tables 13 and 14). Precision data for the method is presented in Table 15. Data reduction was done by computer programme kindly made available by the Geochemistry Department of the University of Cape Town. These programs calculated working curves from the standards and make the necessary corrections for spectral line interference, dead time and matrix effects.

Mass absorption data used in the analysis of Rb, Sr, Zr, Y and Nd were obtained by direct measurement using Nd K_a radiation as described by Jenkins and de Vries (1972). For Ce, Nb, La, Ba and Cl this method is inappropriate and coefficients using Birks' values were obtained by computer programme. The chemical analyses are presented in Tables 16, 17 and 18.

It will be noted that certain analyses sum to rather low totals. These are all of carbonatitic rocks with a high calcium and volatile content. A method was developed whereby these samples were diluted with 50 per cent pure silica, analysed and the analyses corrected afterwards. Although this method improved the analyses the totals were still low. Several samples were re-analysed with little improvement of the results. They were also analysed together with batches of silica-rich rocks, most of which gave satisfactory totals. The only explanations to account for the low totals are:

1. that volatiles were only partly driven off during pre-heating which resulted in a too low LOI value and therefore a low total (ignition temperatures had to be kept below 900^{o}C as most of the carbonatite samples reacted with the vitreosil crucibles at higher temperatures).
2. that some elements remained undetected.

The first possibility is preferred.

TABLE 11: Analytical conditions : MAJOR ELEMENTS

Element	Na	Mg	Al	Si	P	K	Ca	Ti	Mn	Fe
Atom. No.	11	12	13	14	15	19	20	22	25	26
Sample type	P.B.	Fusion disc →								
Kv	50	50	50	50	50	40	40	50	60	50
mA	40	35	30	25	30	20	15	20	40	20
Target	Cr →								W	W
Collimator	coarse	fine	coarse →					fine →		
Crystal	RbAp	RbAp	PET	PET	PET	PET	LiF (200)	LiF (200)	LiF (220)	LiF (200)
Detector	flow counter →									
Voltage (EHT)	1750 →									
Lower level	260	260	240	240	300	220	220	260	320	300
Channel width	320	240	360	300	300	360	340	280	200	280
Counting time (sec)	100	200	20	20	100	10	10	20	100	10
Vacuum	yes →									

P.B. = Pressed briquette (10 tons/sq.inch)

TABLE 12: Analytical conditions : TRACE ELEMENTS

Element	Rb	Sr	Y	Zr	Nb	Ce	Nd	La	Ba	Cl
Atom. No.	37	38	39	40	41	58	60	57	56	27
Sample type	pressed powder briquette, 4 gram 7 ton/sq.inch									
Target	W →									Cr
Kv	40	40	40	40	40	50	50	50	50	50
mA	35	35	35	35	35	40	40	40	40	40
Detector	scintillation →					flow →				
Collimator	fine →								coarse →	
Crystal	LiF (220) →									PET
Counting time (sec)	100	100	100	100	200	200	200	200	200	200

TABLE 13: Adopted values for X-ray fluorescence standards : MAJOR ELEMENTS

Standard	SiO_2	TiO_2	Al_2O_3	Fe_2O_3 +	MnO	MgO	CaO	K_2O	Na_2O	P_2O_5
GSP-1	67,94	0,67	15,27	4,30	0,04	0,99	2,03	5,58	2,80	0,2
AGV-1	59,08	1,05	17,06	6,79	0,10	1,52	4,97	2,89	4,24	0,49
BCR-1	54,50	2,20	13,61	13,40	0,18	3,46	6,92	1,70	3,27	0,36
NIM-P	51,15	0,20	4,20	12,70	0,22	25,25	2,69	0,09		0,02
PCC-1	41,88	0,02	0,72	8,23	0,12	43,22	0,49	0,01		0,02
NIM-D	38,96	0,02	0,40	17,00	0,22	40,43	0,27	0,02		0,03
DTS-1	40,50	0,01	24,49	8,64	0,11	9,80	0,15	0,00		0,00

+ Fe_2O_3 as total iron

TABLE 14: Adopted values for X-ray fluorescence standards : TRACE ELEMENTS

Standard	Rb	Sr	Y	Zr	Nb	Ce	Nd	La	Ba	Cl
BCR-1	46,7	328	33,4	192	11,3	53	29	23	725	50
GSP-1	252	235	25,4	550	25,4	400	190	180	1335	300
G-2	166	475	10,5	335	11,0	150	60	96	1920	
NIM-G	315	9,1	115	280	54				123	600
NIM-D										400
NIM-P										100
NIM-N										100

TABLE 15: Precision data for X-ray fluorescence methods

MAJOR ELEMENTS

based on 14 analyses of sample INHST 1 (granite)			
	$\bar{x}$	s	c
SiO_2	70,25	0,44	0,63
Al_2O_3	13,76	0,20	1,45
TiO_2	0,53	0,01	1,89
Fe_2O_3	3,71	0,07	1,89
MnO	0,051	0,003	5,58
MgO	1,07	0,08	7,48
CaO	1,55	0,03	1,94
Na_2O	2,77	0,11	3,97
K_2O	4,55	0,08	1,76
P_2O_5	0,21	0,02	9,52

INHST 1 has been prepared from 10kg fresh rock of the Darling granite batholith and is used as a reference sample in the analytical laboratory of the Geology Department of the University of Stellenbosch.

TRACE ELEMENTS

	%	s
Rb	2,00	1,73
Sr	1,58	2,18
Y	2,32	1,96
Nb	1,85	3,25
Zr	2,34	1,76
Ce	1,63	1,72
La	1,68	1,76
Nd	2,36	2,67
Ba	2,91	2,13
Cl	3,61	3,19

$\bar{x}$ average weight per cent

s standard deviation

c coefficient of variation

% average percentage difference between 65 duplicate analyses.

2. Electron microprobe method

i) Analysis of Fe-oxide minerals

Analytical conditions : Instrument - Cambridge Geoscan 5
Accelerating voltage - 20kv
Current - 0,5 μA
Beam diameter - 1-2 μm
Counting time - Mg(100 sec), other elements (10 sec.)
Corrections - background, deadtime, absorption, atomic number, fluorescence by computer programme

Standards used : Fe, Ti, Mn, V - pure metals
Mg - periclase (Mg=60,32 wt%)
Ca - wollastonite (Ca=34,42 wt%)

ii) Analysis of silicate minerals

Analytical conditions : Instrument - JEOL SEM
Accelerating voltage - 20 kv
Current - 0,5 μA
Beam diameter - 2 μm
Counting time - Mg = 200 s
- others = 100 s
Corrections - as above, using program ABFAN (Geophysical Laboratory, Carnegie Institution of Washington)

Standards used : Mg, Al, Ti, Fe - Kakanui hornblende*
Na - jadeite^f
Si, Ca - wollastonite^f
K - orthoclase^f
P,F,Cl - apatite USNM 104021*
reference standard - Juan de Fuco basaltic glass*

*samples supplied by Dr. Jarosewich, Smithsonian Institution of Washington.

^{f}stoichiometric composition assumed

3. Wet chemical analysis

Carbon dioxide

This compound was determined, in triplicate where necessary, using the laborious absorption method as described by Bennett and Hawley (1965). Ascarite was used as absorber.

Ferrous iron

Ferrous iron was determined by titrimetic procedures using the permanganate method described by Maxwell (1973). No acceptable precision could be achieved when analysing CO_3^{2-}-rich rocks with low FeO content. The excessive development of CO_2 during digestion probably caused the pH to increase to such an extent that the indicator became inactive. The abovementioned method was therefore adjusted for the analysis of CO_3-rich rocks by increasing the amount of sample to 1 gram and by using 10cc concentrated H_2SO_4 to adjust the pH.

Fluorine

The low concentration of fluorine in alkaline rocks (usually less than 1 wt%) necessitated the use of a method with a detection limit better than that of the normally used photometric or X-ray fluorescence methods. Although unconventional, the pyrohydrolitic method of fluorine determination was attempted. This method proved to be much more elegant and with a better precision than those normally used. Precision data are given below. The apparatus used is illustrated in Fig. 80.

Precision data for the pyrohydrolitic method of fluorine determination.

Sample Number	K4
Number of analyses	8
Mean wt % F	0,063
Standard deviation	0,009
Coefficient of variation	14,29

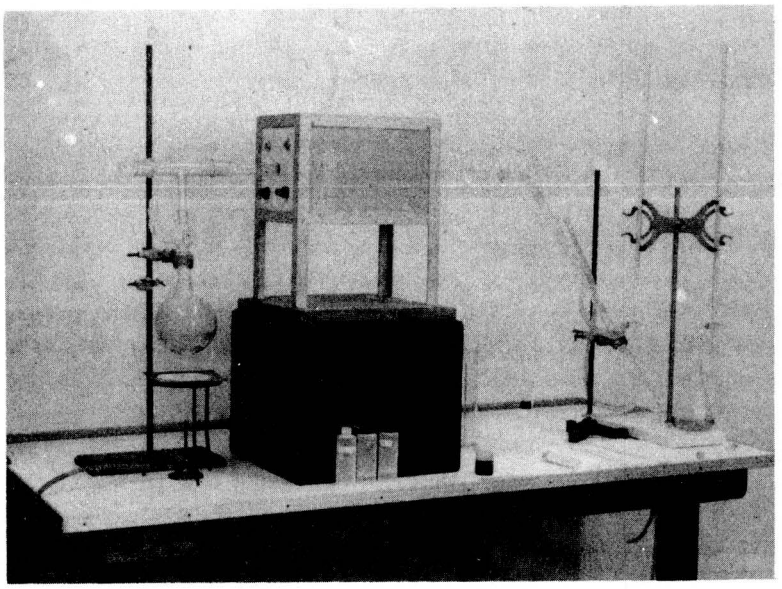

Fig. 80: Apparatus used for the pyrohydrolitic determination of fluorine

The following description of the method is from Bennett and Hawley (1965)

PROCEDURE

The weight of material used for the determination should be varied with the nature of the sample and the V_2O_5 kept at more than about 50 times the anticipated weight of fluorine. Suggested weights are:

Cornish stones	0·2 g
Bodies	0·5 g
Feldspars	1·0 g
Lepidolites, etc. (> 2%F)	0·1 g

Accurately weigh the appropriate amount of the finely ground, dried (110°C) sample and 0·2 g of vanadium pentoxide. Mix the sample and the vanadium pentoxide by grinding in an agate mortar, and transfer the mixture to a platinum boat.

Meanwhile heat the furnace to 800°C and boil the water in the flask, allowing the steam to dissipate to the atmosphere.

Insert the platinum boat into the centre of the furnace and rapidly replace plugs D and C in that order. Increase the temperature of the furnace to 850°C while passing steam at a rate equivalent to 4–5 ml of condensate per min.

Collect 50 ml of the distillate in the polythene bottle and change the receiver. Repeat this collection; for most materials a total of 100 ml is normally sufficient.

Transfer each 50-ml distillate to a 500-ml conical flask marked to indicate a volume of 90 ml. Add 1 drop of phenolphthalein indicator, followed by sodium hydroxide solution (0·4%), drop by drop, until a permanent pink colour is obtained. Adjust the volume to 90 ml.

Add 10 ml of starch indicator, followed by diluted perchloric acid (1+9) drop by drop, until the colour is discharged, and add 1 drop in excess. Then add 0·5 ml of chloroacetic acid buffer solution (17), followed by 5 drops of Alizarin red S indicator. Titrate with standard thorium nitrate solution (approx. 0·1N) until the first appearance of a faint pinkish tinge.

Calculate the fluorine content of the distillates, and from the total the fluorine content of the sample.

BLANK DETERMINATION

A blank determination should be carried out as above but omitting the sample. Normally half a drop (0·02 ml) of thorium nitrate solution per titration suffices.

It was found that a few adjustments improved the analysis of alkaline and carbonatitic rocks.

1. At least one gram of material must be accurately weighed.
2. The use of silica glass tubes instead of platinum boats did not affect the analysis.
3. Titration with a 0, 01 N thorium nitrate solution instead of the 0, 1 N solution is necessary to improve the precision at such low concentrations.
4. The insertion of a piece of glass wool at the lower end of the con= denser assures that all of the water vapour condenses before leaving the apparatus. The glass wool must be brought over into the distil= late before the titration.

Calculation:

Fluoride solution :- 1,1050 g NaF gives a solution with a concentration of 0,05264 mol/l

Standarization of Thorium nitrate solution:-

$$1 \text{ mol } F^- = 6 \text{ mol } Th^{+4}$$

$$\text{conc. } F^- \times \text{vol } F^- = 6 \times \text{conc. } Th^{+4} + \text{vol } Th^{+4}$$

$$\text{conc. } Th^{+4} = \frac{\text{conc. } F^- \times \text{vol } F^-}{\text{vol } Th^{+4} \times 6} \text{ mol/l}$$

Titration of distillate:- (say volume = V1)

$$\text{mol } F^- \text{ in distillate} = 6 \times \text{conc. } Th^{+4} \times V$$

$$\text{mass F} = 19{,}998 \times \text{mol } F^-$$

$$\text{weight \% F in X g sample} = \frac{\text{mass F}}{X} \times 100$$

(NOTE: $ThF_6^{=}$ forms a stable complex during titration. At the endpoint Th forms a pink complex with Alizarin S)

Table 16. Alkaline rocks

Sample No.	Et 1	Et 3	Et 4	Et 5	Et 6	Et 7
SiO_2	55,38	51,11	53,56	53,38	56,43	50,25
TiO_2	,87	,93	,24	,35	1,15	1,70
Al_2O_3	18,78	19,75	21,52	22,48	18,25	19,39
Fe_2O_3	2,15	2,26	2,22	,97	2,24	2,01
FeO	4,14	4,78	2,02	2,59	2,98	5,35
MnO	,25	,20	,14	,12	,21	,20
MgO	,87	2,60	,88	1,31	1,42	2,20
CaO	2,33	4,78	1,45	1,25	2,06	5,30
Na_2O	8,20	8,91	10,95	11,18	8,68	8,46
K_2O	5,33	3,51	4,82	5,31	5,14	3,31
P_2O_5	,29	,58	,23	,24	,19	,63
CO_2	,25	,29	tr	,05	tr	,09
H_2O^-	,36	,22	,51	,11	,13	,20
H_2O^+	,60	,52	1,84	,80	,89	1,06
F	n.d.	,14	n.d.	n.d.	,17	,12
	99,80	100,48	100,38	100,09	99,94	100,18
-O (F,Cl)		,10	,42	,23	,19	,10
total	99,80	100,38	99,96	99,86	99,73	100,08
F	980	1500	350	n.d.	1760	1230
Rb	250	82	118	220	220	120
Sr	179	860	318	72	325	868
Ba	1554	1634	1120	438	1148	1678
Y	63	39	22	15	67	60
Zr	783	336	223	149	465	374
Nb	342	143	87	78	301	121
La	288	166	122	87	227	140
Ce	475	259	190	143	378	235
Nd	149	81	59	43	119	79
Cl	2192	2124	5688	6044	4080	1934
K/Rb	176	355	339	200	193	228
Ce/Y	7,54	6,64	8,64	9,53	5,64	3,92

Table 16. Continued

Sample No.	Et 8	Et 12	Et 13	K 1	K 3	K 4
SiO_2	53,68	52,77	49,73	45,85	61,61	61,01
TiO_2	1,29	,29	,80	1,92	1,68	1,35
Al_2O_3	17,58	19,75	19,73	14,51	16,78	17,08
Fe_2O_3	2,50	1,89	2,16	2,56	,36	,45
FeO	5,18	2,92	4,38	8,75	,07	-
MnO	,25	,27	,18	,19	,03	,02
MgO	1,99	1,40	3,00	7,50	,21	,36
CaO	4,98	2,24	4,26	11,14	2,06	,00
Na_2O	6,55	8,65	9,97	3,65	,77	,96
K_2O	3,52	4,70	3,44	1,19	14,69	13,62
P_2O_5	,50	,13	,50	,59	,12	,14
CO_2	,50	1,11	,35	tr	1,36	,43
H_2O^-	,38	,74	,18	,45	,35	,19
H_2O^+	1,33	3,84	1,02	1,21	1,74	1,91
F	n.d.	n.d.	,19	n.d.	n.d.	n.d.
	100,23	99,59	99,53	99,51	100,40	99,52
-O (F,Cl)		,09	,08			
total	100,23	99.50	99,45	99,51	100,40	99,52
F	n.d.	n.d.	1910	n.d.	340	620
Rb	75	300	64	26	153	313
Sr	517	154	849	830	216	380
Ba	1384	399	1673	683	1838	2135
Y	77	91	33	27	12	35
Zr	841	1284	231	180	9	980
Nb	230	425	104	51	1835	735
La	258	418	166	43	65	104
Ce	408	603	263	92	96	354
Nd	143	166	64	47	35	47
Cl	947	4069	2947	453	243	247
K/Rb	389	130	446	379	797	361
Ce/Y	5,30	6,63	7,97	3,41	8,0	10,11

XRF analyses with major elements in wt % and trace elements in ppm.

Sample No.	Locality	Rock type
Et 1	Etaneno	grey nepheline syenite(dyke)
Et 3	Etaneno	core nepheline syenite
Et 4	Etaneno	porhyritic nepheline syenite
Et 5	Etaneno	grey nepheline syenite(dyke)
Et 6	Etaneno	white nepheline syenite
Et 7	Etaneno	grey nepheline syenite
Et 8	Etaneno	grey nepheline syenite
Et 12	Etaneno	sodalite syenite(xenolith)
Et 13	Etaneno	dark nepheline syenite(dyke)
K 1	Kalkfeld	olivine dolerite
K 3	Kalkfeld	fine grained syenite
K 4	Kalkfeld	coarse grained syenite

Table 16 Continued

Sample No.	K 5	K 6	K 10	K 12	K 15
SiO_2	51,06	51,53	60,89	61,97	51,88
TiO_2	,59	,59	,48	,54	,64
Al_2O_3	19,02	18,90	16,79	17,57	21,64
Fe_2O_3	4,26	3,58	2,16	1,75	2,38
FeO	,68	1,19	-	,58	1,70
MnO	,22	,21	,13	,08	,09
MgO	,41	,55	,07	,11	,55
CaO	2,10	3,30	3,89	3,07	,63
Na_2O	9,49	9,02	9,09	7,44	7,89
K_2O	5,99	6,82	,14	3,35	8,39
P_2O_5	,17	,47	,06	,08	,08
CO_2	2,35	2,19	1,83	1,62	,63
H_2O^-	,39	,33	,22	,26	,52
H_2O^+	3,59	2,05	3,37	2,22	2,47
F	n.d.	tr	n.d.	n.d.	tr
	100,29	100,73	99,12	100,64	99,50
-O (F,Cl)					
total					
F		400			290
Rb	115	153	2	62	216
Sr	1614	1502	165	242	951
Ba	678	713	n.d.	840	n.d.
Y	23	26	36	39	7
Zr	893	1558	665	593	650
Nb	394	610	117	86	207
La	275	143	51	78	19
Ce	370	244	88	134	37
Nd	98	89	42	62	14
Cl	269	223	169	184	2460
K/Rb	432	370	581	448	322
Ce/Y	16,09	9,38	2,44	3,44	5,29

Sample No.	Locality	Rock type
K 5	Kalkfeld	nepheline syenite
K 6	Kalkfeld	nepheline syenite(chill phase)
K 10	Kalkfeld	porphyritic syenite(dyke)
K 12	Kalkfeld	syenite porphyry (dyke)
K 15	Kalkfeld	nepheline syenite

Sample No.	K 16	K 19	K 28	Oku 1	Oku 2	Oku 4
SiO_2	55,45	56,16	58,61	56,45	53,65	55,68
TiO_2	,64	,79	,34	,41	1,66	,85
Al_2O_3	18,87	19,00	16,67	20,11	16,43	17,89
Fe_2O_3	4,43	3,17	1,72	1,27	3,92	2,67
FeO	1,72	2,58	-	1,77	5,97	2,31
MnO	,11	,19	,10	,13	,23	,14
MgO	,46	,47	,24	1,18	2,22	1,30
CaO	2,00	1,36	3,65	1,67	4,74	3,34
Na_2O	5,71	6,44	,11	8,47	6,26	8,27
K_2O	8,01	7,45	15,30	5,40	3,80	4,40
P_2O_5	1,35	,03	,61	,22	,78	-
CO_2	1,35	,96	2,09	,51	,05	,99
H_2O^-	,24	,34	,37	,35	,01	,01
H_2O^+	1,80	1,05	,64	2,58	,84	1,90
F	n.d.	tr	tr	tr	n.d.	n.d.
-O (F,Cl)						
total	100,59	99,99	100,45	100,52	100,56	99,75
F		1090	1000	700		
Rb	217	257	188	105	84	97
Sr	406	2002	208	360	478	693
Ba	2193	468	1712	2566	1971	3618
Y	34	17	66	23	46	36
Zr	137	892	21	190	304	245
Nb	128	382	529	65	104	113
La	20	102	174	60	115	109
Ce	36	170	268	120	205	196
Nd	19	49	107	42	91	77
Cl	266	2136	168	396	n.d.	1392
K/Rb	314	240	675	426	375	376
Ce/Y	1,06	10,0	4,06	5,22	4,46	5,44

Sample No.	Locality	Rock type
K 16	Kalkfeld	dolerite
K 19	Kalkfeld	tinguaite(dyke)
K 28	Kalkfeld	feldspathized xenolith in carb.
Oku 1	Okorusu	course grained nepheline syenite
Oku 2	Okorusu	monzonite
Oku 4	Okorusu	non-foliated syenite

Table 16. Continued

Sample No.	Oku 5	Oku 13	Oku 14	Oku 15	Oku 19	Oku 20
SiO_2	55,07	46,22	47,60	53,44	53,48	54,00
TiO_2	,82	,72	,68	,51	,34	,30
Al_2O_3	18,35	16,40	17,07	18,71	23,53	21,63
Fe_2O_3	3,26	4,34	5,27	2,98	3,28	2,02
FeO	2,51	3,05	2,15	1,22	1,26	1,28
MnO	,17	,34	,32	,18	,14	,14
MgO	1,85	2,67	,34	1,09	,56	1,13
CaO	4,03	5,54	5,04	3,66	1,56	1,39
Na_2O	7,12	11,16	7,09	6,90	10,27	10,93
K_2O	3,83	4,30	5,10	7,67	4,20	4,77
P_2O_5	,39	,22	,12	,14	,23	,20
CO_2	,31	,10	1,99	1,22	,39	,89
H_2O^-	,01	,04	,75	,63	,28	,35
H_2O^+	2,05	4,69	4,98	1,49	,89	1,28
F	,11	n.d.	,19	n.d.	tr	n.d.
	99,77	99,79	98,69	99,84	100,41	100,31
-O (F,Cl)	,05		,14	,17		
			,83	,59	,14	,32
total	99,72	99,79	99,38	100,26	100,55	100,63
F	1070				471	
Rb	96	130	169	203	103	104
Sr	737	1388	3006	2098	260	354
Ba	1890	1200	2479	3106	1275	2848
Y	41	10	42	22	23	24
Zr	370	271	347	322	167	198
Nb	128	260	460	232	78	70
La	90	90	146	104	79	69
Ce	132	132	221	183	129	105
Nd	44	44	63	59	42	39
Cl	344	13742	1970	7430	717	n.d.
K/Rb	331	331	250	314	338	380
Ce/Y	3,22	274	5,26	8,32	5,61	4,38

Sample No.	Oku 21	Oku 29	On 12	On 17
SiO_2	45,76	50,32	51,65	46,94
TiO_2	1,13	,69	,53	,05
Al_2O_3	15,41	19,28	19,02	13,42
Fe_2O_3	3,68	3,31	4,53	4,63
FeO	4,46	2,46	2,34	,31
MnO	,18	,21	,09	,77
MgO	5,18	1,98	,47	,41
CaO	8,27	4,61	3,91	11,42
Na_2O	6,64	8,40	5,12	3,52
K_2O	3,15	5,68	8,81	5,36
P_2O_5	,77	,37	,38	1,05
CO_2	1,19	1,76	2,08	n.d.
H_2O^-	,59	,34	1,15	,51
H_2O^+	2,91	,93	,84	9,63
F	,19	n.d.	n.d.	n.d.
	99,51	100,34	100,08	98,02
-O (F,Cl)	,25	,23		
traces	,98	,54	,60	1,02
total	100,24	100,65	100,68	99,04
F	1950			
Rb	112	172	192	95
Sr	1254	1815	1654	1360
Ba	1497	2932	2158	5806
Y	28	34	10	103
Zr	280	393	1190	388
Nb	225	352	286	477
La	126	301	57	234
Ce	207	458	100	449
Nd	81	139	41	203
Cl	7641	10160	69	62
K/Rb	233	273	459	564
Ce/Y	7,39	13,47	10,0	4,36

XRF analyses with major elements in wt % and trace elements in ppm.

Sample No.	Locality	Rock type
Oku 5	Okorusu	foliated syenite
Oku 13	Okorusu	ijolite
Oku 14	Okorusu	fine-grained dark neph.syenite
Oku 15	Okorusu	tinguite(dyke)
Oku 19	Okorusu	nepheline syenite(central plug)
Oku 20	Okorusu	tinguaite(dyke)
Oku 21	Okorusu	tinguaite (dyke)
Oku 29	Okorusu	tinguaite (dyke)
On 12	Ondurakorume	nepheline syenite(juvite)
On 17	Ondurakorume	syenite(weathered ?)

Table 17. Carbonatitic rocks

Sample No.	K 2	K 4a	K 11	K 22	K 13	Oku 18
SiO_2	15,85	1,11	1,64	1,79	2,02	1,22
TiO_2	,99	,21	,14	,18	,03	,01
Al_2O_3	4,83	1,27	,51	1,39	,84	,49
Fe_2O_3	1,54	16,10	5,23	20,64	61,20	3,73
FeO	9,62	3,76	,27	-	-	,44
MnO	1,91	3,32	1,27	4,42	7,52	,58
MgO	5,02	6,10	2,94	4,84	-	,68
CaO	23,16	27,00	37,53	24,54	7,96	47,53
Na_2O	1,23	-	9,40	-	-	-
K_2O	3,24	-	2,33	-	-	,04
P_2O_5	1,04	2,34	1,77	,44	,16	1,34
CO_2	22,13	31,50	31,01	27,31	n.d.	36,36
H_2O^-	,34	,42	,24	1,86	4,27	,49
H_2O^+	1,34	,76	1,10	2,37	LOI 11,79	1,21
F	tr	n.d.	tr	,11	n.d.	n.d.
	92,24	93,89	95,38	89,88	95,80	94,12
-O (F,Cl)				,05		
traces	5,94	4,50	4,28	8,44	2,69	4,25
total	98,19	98,39	99,66	98,28	98,49	98,37
F	440		235	1200		
Rb	145	-	-	-	-	2
Sr	24686	32140	14656	36940	5263	16299
Ba	1200	4200	804	3763	16970	8274
Y	223	190	217	110	123	194
Zr	242	30	72	5	35	55
Nb	975	500	1830	23	49	355
La	4311	1203	2451	5239	574	1983
Ce	5782	6353	4545	7955	2013	3154
Nd	1456	1117	1642	2396	1386	832
Cl	18	n.d.	401	-	n.d.	-
K/Rb	187	-	-	-	-	174
Ce/Y	25,93	33,44	20,94	72,32	16,37	16,26

Sample No.	On 25	Os 1	Os 4	Os 5	Oku 6	Oku 12
SiO_2	1,00	4,63	7,28	32,18	16,40	2,83
TiO_2	,01	,10	,22	,54	1,49	3,25
Al_2O_3	-	1,22	,21	8,34	3,87	,75
Fe_2O_3	9,07	59,48	6,94	9,64	14,43	79,71
FeO	1,54	-	,85	-	2,53	-
MnO	2,60	4,41	1,28	1,55	,44	,42
MgO	6,37	2,39	1,70	,77	2,62	-
CaO	34,04	8,48	40,67	18,11	26,41	1,31
Na_2O	-	-	-	-	,38	3,28
K_2O	-	,12	-	7,15	2,12	,02
P_2O_5	11,06	,05	7,08	,06	2,66	,18
CO_2	29,55	13,42	27,04	15,85	23,10	n.d.
H_2O^-	,53	1,60	,73	1,52	,45	,75
H_2O^+	,31	,75	1,52	1,32	,71	LOI 5,39
F						
	96,58	96,65	98,07	97,03	97,61	97,89
-O (F,Cl)						
traces	4,63	2,78	2,55	2,04	2,77	1,87
total	100,71	99,43	98,07	99,07	100,38	99,76
F						
Rb	-	3	1	114	60	8
Sr	21213	8410	3629	855	9866	412
Ba	812	13995	1879	12317	2514	16765
Y	425	49	961	19	64	23
Zr	611	248	165	27	50	7
Nb	65	55	868	225	1961	203
La	2403	504	1907	1021	1172	410
Ce	4757	946	3135	1420	2087	232
Nd	1922	621	1024	435	490	155
Cl	26	28	74	2	94	n.d.
K/Rb	-	-	-	-	293	25,9
Ce/Y	11,19	19,31	3,26	74,74	32,61	10,09

XRF analyses with major elements in wt % and trace elements in ppm.

Sample No.	Locality	Rock type
K 2	Kalkfeld	micaceous sövite
K 4a	Kalkfeld	ankeritic sövite(vein)
K 11	Kalkfeld	grey sövite
K 22	Kalkfeld	ankeritic sövite(plug)
K 13	Kalkfeld	hematite ore
Oku 18	Okorusu	sövite
On 25	Ondurakorume	apatite beforsite
Os 1	Osongombo	iron ore
Os 4	Osongombo	beforsite
Os 5	Osongombo	beforsite(vein)
Oku 6	Okorusu	sövite
Oku 12	Okorusu	iron ore

Table 17. Continued

Sample No.	On 2	On 4	On 6	On 7	On 8	On 9	On 10
SiO_2	17,27	9,57	38,83	5,56	2,94	1,72	4,68
TiO_2	,86	,03	1,41	,01	,04	,02	,03
Al_2O_3	5,90	,24	11,63	,50	,59	,23	,00
Fe_2O_3	5,02	16,74	3,97	1,91	4,67	1,95	1,32
FeO	16,83	16,24	6,82	15,85	4,75	5,53	5,16
MnO	2,33	5,41	2,51	4,21	3,63	2,16	1,21
MgO	5,46	5,73	10,67	7,35	8,09	4,96	2,06
CaO	15,53	10,57	10,73	18,12	28,20	35,81	42,29
Na_2O	,03	1,01	,81	,00	,00	,00	,00
K_2O	3,45	,01	1,49	,12	,03	,00	,01
P_2O_5	2,86	1,87	,34	4,60	4,78	7,37	4,36
CO_2	15,57	23,18	4,80	26,13	30,76	34,68	33,01
H_2O^-	,37	,74	2,39	,30	,71	,57	1,35
H_2O^+	2,87	1,10	2,23	5,36	1,61	,43	,57
F	n.d.	,62	n.d.	n.d.	n.d.	n.d.	n.d.
		93,06	98,62	90,02	90,79	95,43	96,05
-O (F,Cl)		,26					
	4,26	8,10	1,76	7,39	7,56	4,08	3,83
total	98,31	100,90	100,38	97,41	98,35	99,51	99,88
F							
Rb	98	-	46	-	-	-	33
Sr	12230	42685	1452	29761	33874	23967	16738
Ba	16849	2804	14222	5018	3801	2089	2235
Y	254	83	25	235	276	285	275
Zr	388	800	130	816	785	573	479
Nb	1914	706	140	493	1005	768	1440
La	1104	4066	90	4911	2780	1916	1283
Ce	2039	6181	154	6966	5313	4094	2640
Nd	821	1436	71	1693	2044	1748	1169
Cl	18	-	68	-	-	-	-
K/Rb	245	-	324	-	-		-
Ce/Y	8,03	74,47	6,16	29,64	19,25	14,36	9,60

Sample No.	Locality	Rock type
On 2	Ondurakorume	micaceous beforsite
On 4	Ondurakorume	rare earth beforsite
On 6	Ondurakorume	pisolitic beforsite
On 7	Ondurakorume	rare earth beforsite
On 8	Ondurakorume	white sövite
On 9	Ondurakorume	apatite beforsite
On 10	Ondurakorume	white sövite

Table 18. Metasomatic rocks and Salem granite

Sample No.	On 13	K 17a	K 17b	K 18a	K 26	K 85a
SiO_2	65,96	59,86	71,87	65,84	70,16	67,75
TiO_2	,30	,15	,13	,93	,29	,42
Al_2O_3	14,10	12,00	13,22	18,32	13,36	13,46
Fe_2O_3	2,54	3,53	,77	1,26	1,48	4,16
FeO	-	2,34	,41	,02	,98	-
MnO	,07	,31	,03	,03	,08	,11
MgO	,41	1,12	,30	,36	1,04	,62
CaO	2,08	5,90	1,79	,16	1,30	1,56
Na_2O	3,34	3,68	3,79	6,80	3,87	4,27
K_2O	9,79	7,11	6,25	6,49	5,98	6,20
P_2O_5	,24	,32	,02	-	,06	,12
CO_2	n.d.	2,10	,77	n.d.	,75	n.d.
H_2O^-	,05	,19	,25	,04	,39	,05
H_2O^+	(LOI)1,50	,30	,37	(LOI) ,36	,37	(LOI)1,16
F	n.d	n.d.	n.d.	n.d.	,23	n.d.
					,10	
-O (F,Cl)						
total	100,38	98,61	99,97	100,61	100,24	99,88
F		720	1090		2330	
Rb		333	217		211	
Sr		904	406		483	
Ba		512	633		1091	
Y		81	34		43	
Zr		34	136		306	
Nb		125	18		26	
La		137	93		175	
Ce		266	150		303	
Nd		98	53		110	
Cl		523	446		440	
K/Rb		177	239		235	
Ce/Y		3,28	4,41		7,05	

Sample No.	Oku 32a	Oku 32b	Oku 33a	Oku 33b	Oku 34
SiO_2	27,09	37,42	47,94	51,69	64,71
TiO_2	,27	,24	,34	,32	,58
Al_2O_3	5,14	5,82	5,26	5,08	9,97
Fe_2O_3	1,27	1,48	5,00	1,63	2,71
FeO	1,50	1,55	4,87	1,49	1,65
MnO	,53	,31	,65	,56	,11
MgO	1,12	1,34	4,86	1,17	2,47
CaO	27,62	22,11	18,25	29,39	5,64
Na_2O	,01	-	2,16	,29	4,97
K_2O	4,27	5,04	4,34	4,41	2,48
P_2O_5	4,20	,13	1,06	,16	,18
CO_2	22,37	21,56	3,03	2,60	2,69
H_2O^-	,29	,48	,16	,15	,32
H_2O^+	3,25	,80	1,53	1,34	,95
F	3,11	n.d.	n.d.	n.d.	n.d.
-O (F,Cl)	1,31				
total	100,73	98,28	99,45	100,28	99,43
F					
Rb	101	113	100	80	75
Sr	1829	4321	3276	1827	522
Ba	1064	2731	1777	1012	2454
Y	78	72	20	56	53
Zr	80	413	178	123	189
Nb	240	109	188	506	17
La	85	1333	156	102	135
Ce	152	1932	270	197	229
Nd	56	422	82	72	90
Cl	79	73	233	279	238
K/Rb	350	370	360	457	274
Ce/Y	1,95	26,83	13,50	3,52	4,32

XRF analyses with major elements in wt % and trace elements in ppm.

Sample No.	Locality	Rock type
On 13	Ondurakorume	fenitized granite
K 17a	Kalkfeld	fenitized granite
K 17b	Kalkfeld	fenitized granite
K 18a	Kalkfeld	fenitized syenite
K 26	Kalkfeld	granite
K 85a	Kalkfeld	fenitized granite

Sample No.	Locality	Rock type
Oku 32a	Okorusu	bleached pyroxene fenite
Oku 32b	Okorusu	feldspathised pyroxene fenite
Oku 33a	Okorusu	pyroxene fenite
Oku 33b	Okorusu	fenitized felspathic sandstone
Oku 34	Okorusu	fenitized feldspathic sandstone

Table 18. Continued

Sample No.	Oku 36	Oku 37	S 1
SiO_2	37,99	44,88	71,13
TiO_2	,39	,29	,32
Al_2O_3	10,73	4,97	14,00
Fe_2O_3	9,99	1,60	,41
FeO	-	,30	2,01
MnO	,37	,12	,03
MgO	3,72	2,36	,49
CaO	9,45	42,20	1,45
Na_2O	,14	-	2,96
K_2O	9,38	-	6,04
P_2O_5	,05	,03	,04
CO_2	10,78	2,79	n.d.
H_2O^-	1,10	,15	-
H_2O^+	2,83	,31	(LOI),86
F	2,43	n.d.	n.d.
-O (F,Cl)	1,02		
	,68		
total	99,01	100,04	99,74
Rb	180	-	
Sr	1645	142	
Ba	4338	91	
Y	62	14	
Zr	559	105	
Nb	172	-	
La	439	18	
Ce	635	33	
Nd	162	14	
Cl	805	368	
K/Rb	432		
Ce/Y	10,24		

Sample No.	Locality	Rock type
Oku 36	Okorusu	feldspathic breccia
Oku 37	Okorusu	feldspathic quartzite
S 1	Kalkfeld	Salem granite

C. X-RAY DIFFRACTION

Order-disorder and compositional variations in the alkali feldspars were investigated by means of X-ray diffraction. X-ray powder diffractometer scans were made on a Philips PW 1411 unit fitted with a LiF(200) crystal monochromator. Goniometer scan speed was $1/4^{o}$ per minute with a chart speed of 25mm per minute. Peak positions were measured as near as possible to the top of the peaks.

Feldspar concentrates were obtained either by handpicking or, in a few cases by magnetic methods. The latter produced a feldspar/nepheline mixture. The nepheline peaks on diffractograms of these mixtures could be identified and did not interfere with any of the measurements. $KBrO_3$ was used as internal standard and was mixed with about one gram of feldspar concentrate, ground to -300 mesh and back-packed against a glass plate contained in a standard aluminium X-ray diffractometer mount. Samples were twice packed and each run two or three times over the following angular distances:

2 θ range	Calibration peak of $KBrO_3$	Feldspar peaks measured
19,5 - 25,0	20,212 (101)	$(\bar{2}01)$
38,0 - 39,5		$(\bar{1}13)$
40,5 - 42,5	41,088 (202)	(060)
50,0 - 52,0	51,476 (112)	$(\bar{2}04)$

No significant variation in peak intensities was noted and 2 θ values did not differ by more than $0,01^{o}$. Seven scans of one sample (Oku 4) were made in order to estimate the precision of the method. These results were satisfactory and are given in Table 10 below.

TABLE 19: Precision data for X-ray diffraction scans of the alkali feldspar from sample number Oku 4

	$(\bar{2}01)$	(060)	$(\bar{2}04)$
	21,04	41,71	50,65
	21,03	41,72	50,67
	21,04	41,75	50,68
	21,06	41,73	50,65
	21,02	41,72	50,64
	21,03	41,75	50,65
	21,05	41,74	50,66
$\bar{x}$	21,04	41,73	50,66
s	,01	,01	,01

D. SAMPLE DESCRIPTIONS AND LOCALITIES

1. Kalkfeld

Sample number	Rock type	Sample number	Rock type
K-1	Olivine dolerite dyke	K-14	Tachylite vein
K-2	Micaceous sövite	K-15	Nepheline syenite
K-3	Fine-grained syenite	K-16	Dolerite
K-4	Coarse-grained syenite	K-17a	Fenitized granite (2,712)
K-5	Nepheline syenite	K-17	Fenitized granite (2,703)
K-6	Nepheline syenite chill phase	K-18	Fenitized syenite (2,698)
K-10	Porphyritic syenite dyke	K-19	Tinguaite
K-11	Grey sövite	K-22	Brown apatite-rich sövite
K-12	Porphyritic syenite dyke	K-26	Granite
		K-28	Feldspathic xenolith in carbonatite (2,890)

Density of samples given in brackets.

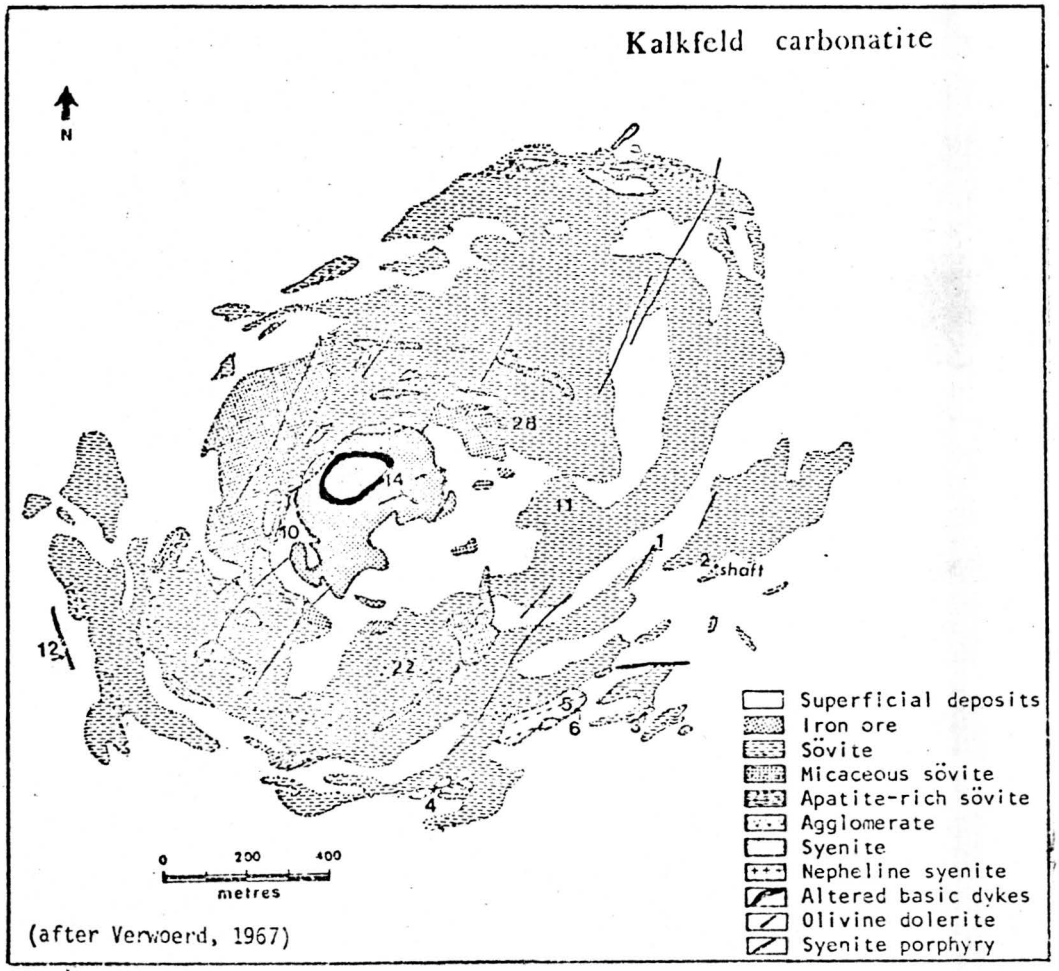

Fig. 81: Sample localities at Kalkfeld carbonatite

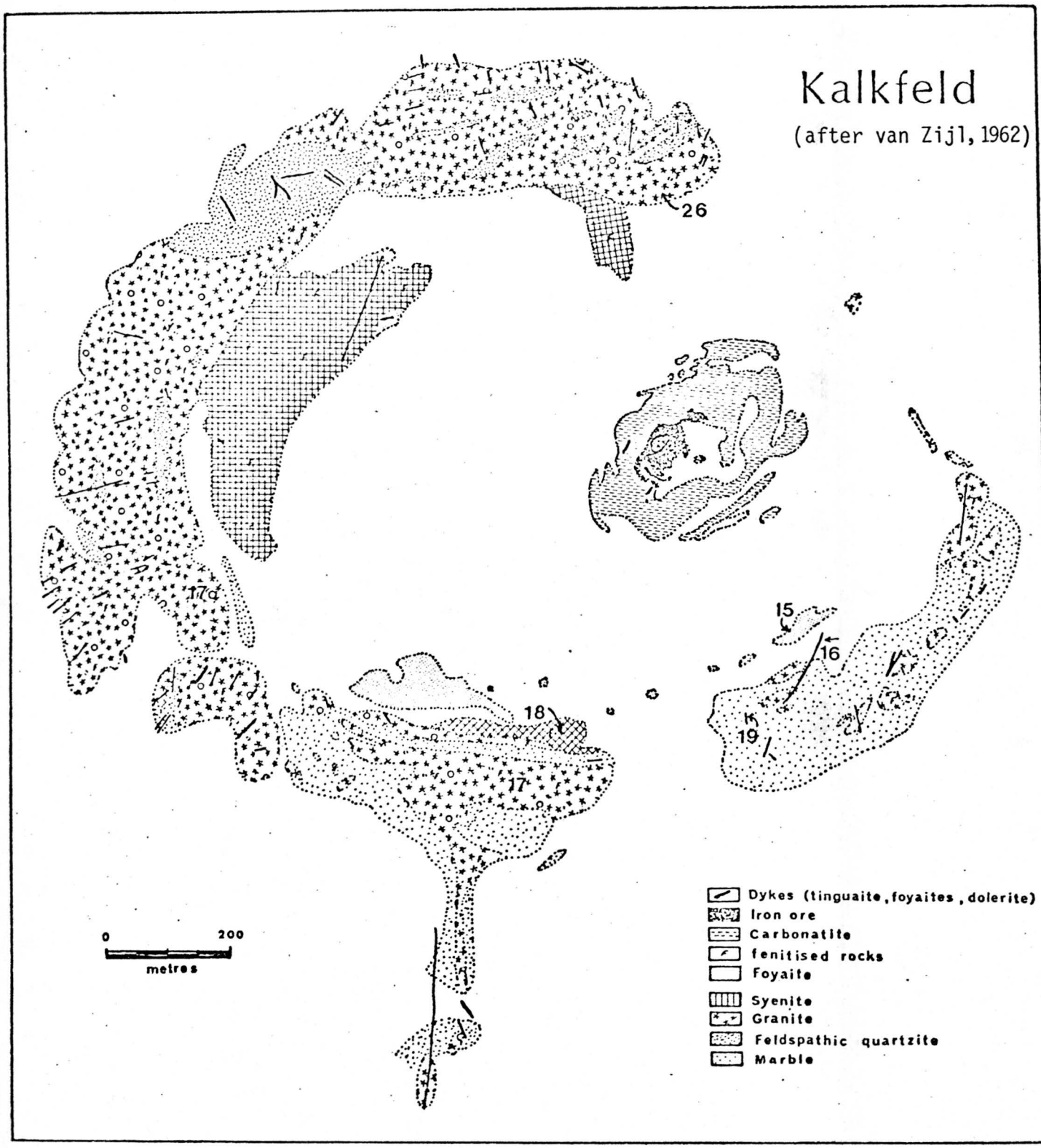

Fig. 82: Sample localities at Kalkfeld complex.

2. Osongombo

Os-1	Iron ore
Os-4	Beforsite
Os-5	Beforsite vein

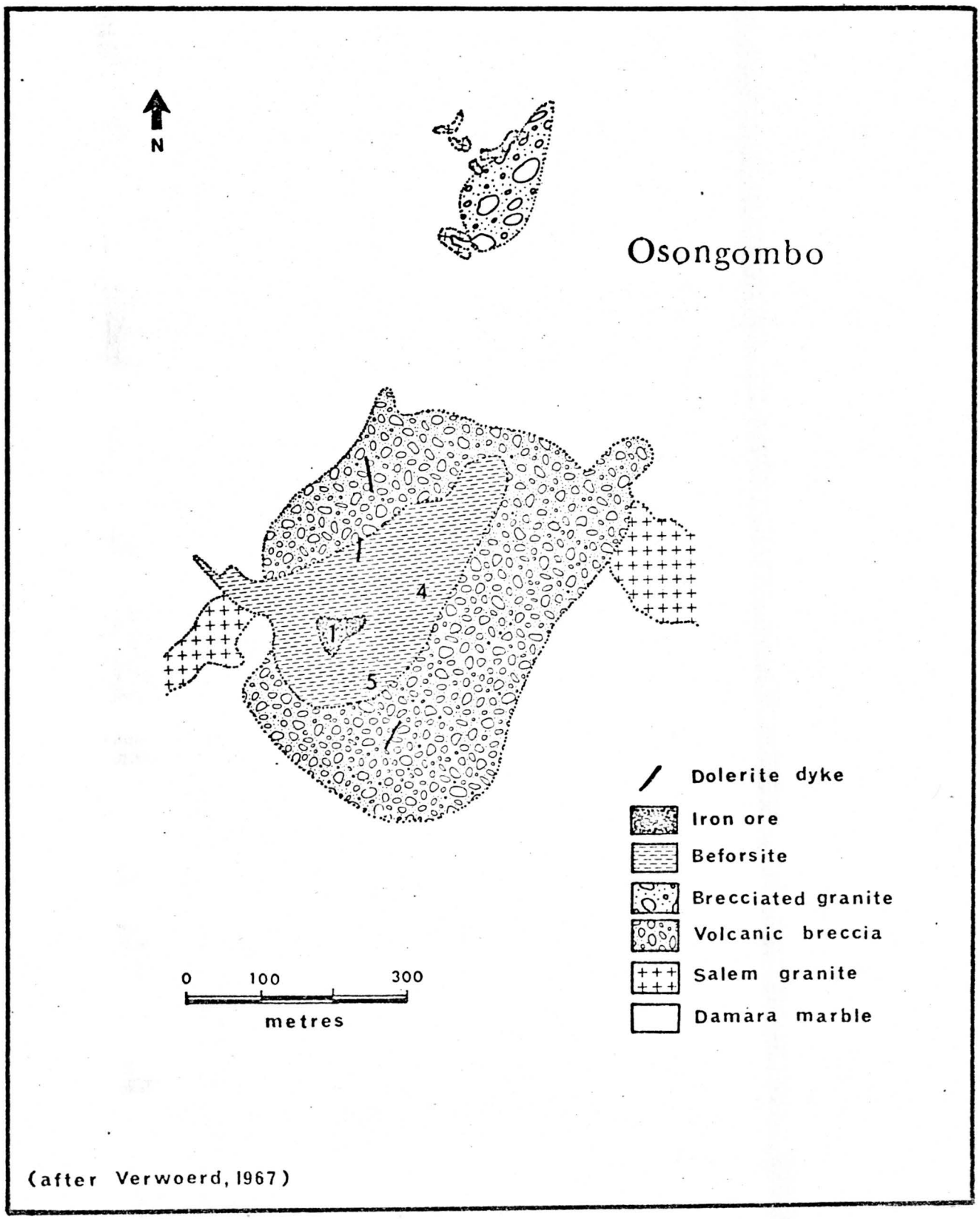

Fig. 83: Sample localities at Osongombo.

3. Etaneno

Sample Numbers	Rock type	Sample Numbers	Rock type
Et-1	Grey nepheline syenite (dyke)	Et-6	White nepheline syenite
Et-3	Core nepheline syenite	Et-7	Fine-grained core nepheline syenite
Et-4	Porphyritic nepheline syenite	Et-8	Grey nepheline syenite
Et-5	Grey nepheline syenite (dyke)	Et-11	Sodalite syenite
		Et-13	Dark nepheline syenite (dyke)

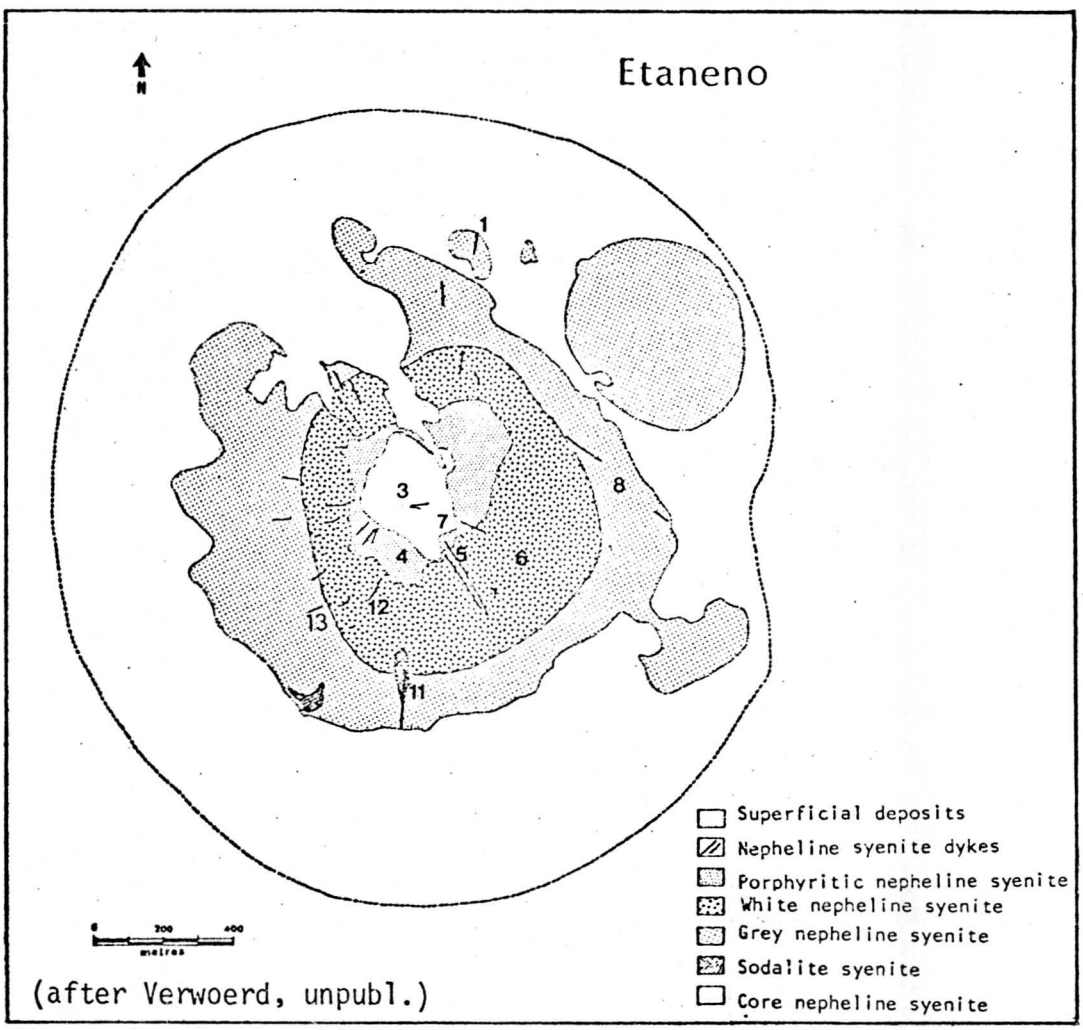

Fig. 84: Sample localities at Etaneno.

4. Okorusu

Sample number	Rock type
Oku-1	Coarse-grained nepheline syenite
Oku-2	Monzonite
Oku-4	Unfoliated syenite
Oku-5	Foliated syenite
Oku-6	Carbonatite
Oku-12	Magnetite-rich carbonatite
Oku-13	Fine-grained dark nepheline syenite
Oku-14	Ijolite
Oku-15	Nepheline syenite (dyke)
Oku-18	Carbonatite
Oku-19	Nepheline syenite (centre of complex)
Oku-20	Tinguaite (centre of complex)
Oku-21	Tinguaite
Oku-26	Altered tinguaite dyke (2m from fluorite vein)(2,648)
Oku-28	Bleached tinguaite dyke (next to fluorite vein)(2,541)
Oku-29	Tinguaite
Oku-32a	Bleached pyroxene fenite (2,727)
Oku-32b	Feldspathized pyroxene fenite (2,635)
Oku-33a	Pyroxene fenite (3,088)
Oku-33b	Calcareous sandstone (2,854)
Oku-34	Fenitized feldspathic sandstone (50m from contact) (2,767)
Oku-35	Fenitized feldspathic sandstone (100m from contact) (2,713)
Oku-36	Brecciated feldspar fenite (2,627)
Oku-37	Unaltered sandstone (3,106)
Oku-40	Carbonatite
Oku-41	Pyroxene fenite
Oku-42	Calcite vein in pyroxene fenite
Oku-43	Feldspathized pyroxene fenite
Oku-44	Ijolite with carbon te globules
Oku-45	Monchiquitic rock with carbonate globules

Density of samples given in brackets.

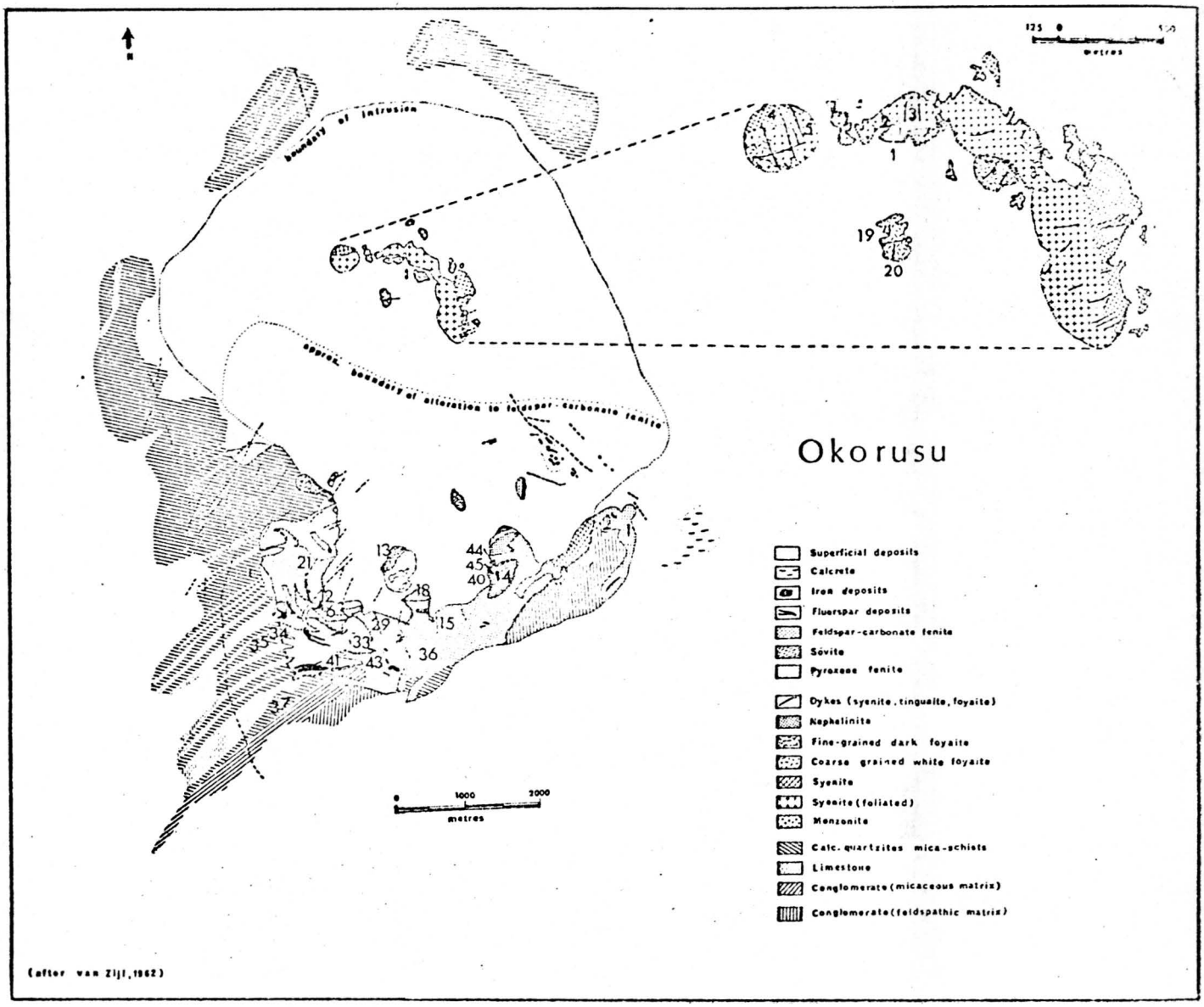

Fig. 85: Sample localities at Okorusu.

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